A GEOLOGICAL INVESTIGATION OF A TERTIARY INTRUSIVE CENTRE IN THE VIDIDALUR-VATNSDALUR AREA, NORTHERN ICELAND : VOL. 2

Richard Newton Annells

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C H A P T E R 3

PETROGRAPHY OF THE INTRUSIVE ROCKS OF THE VIDIDALUR - VATNSDALUR AREA

The intrusive rocks show considerable variation in texture but are all simple assemblages of plagioclase,pyroxene and ore with or without olivine. Quartz and alkali feldspar were found to be major rock-forming minerals only in the acid rocks. Theccompositions of the main rock-forming minerals in the intrusive rocks (as determined by the methods outlined in Chapter 4) are summarized in Fig. 51.

The First and Second Phase rock assemblages show some difference in mineralogy.Olivine was found to be rare in the First Phase basic rocks except as scattered phenocrysts in the eucrites but was seen to be common in the Second Phase basic rocks as a phenocryst or groundmass constituent. Few examples of coarse-grained or acid rocks were found among the Second Phase products, and rocks of these two types were found to be more abundant among the First Phase rocks; this circumstance is felt to be due to the higher level of intrusion and the relatively shallow level of erosion of the Second Phase intrusive suite.

A number of modal analyses (expressed as percentage volumes) are given in this chapter; these represent determinations made on single thin sections, with the exception of that given for the Hólar-Skessusaeti eucrite. The symbol "tr" (trace) in these modes is used in the case of minerals which make up less than 0.1 per cent of a rock by volume and which did not fall beneath the intersection of the microscope crosswires during the determination.

Fig. 51. Summary of the compositions of the main rock-forming minerals in the Vididalur-Vatnsdalur intrusive rocks, showing the contrasted mineralogy of the First and Second Phase rocks; the vertical lines indicate the presence of a given mineral. The arrangement of the data in order of decreasing anorthite content of plagioclase is not intended to imply the existence of a continuous fractionation sequence. Plagioclase compositions in brackets represent microphenocryst cores.

Phase	Rock type	Plagioclase	Clinopyroxene Ca-rich	Clinopyroxene Ca-poor	Ortho-pyroxene	Olivine	Ore	Amphibole	Alkali feldspar	Quartz as phenocrysts
SECOND PHASE	Dacite	An_{37-33}	$Ca_{44}Mg_{22.5}Fe_{33.5}$				│		│	
	Type 3 cone-sheet	An_{60}	│	│		│	│			
	Gabbro	An_{70}	$Ca_{38}Mg_{38.5}Fe_{23.5}$	│		│	│			
	Type 1 & 2 cone-sheets	$An_{90(78)}$	$Ca_{39.5}Mg_{37.5}Fe_{23}$	│		Fa_{20-62}	│			
FIRST PHASE	Granophyre	An_{31}	Aegirine-augite			│	│	│	│	│
	Felsites and pitchstones	An_{41-33}	$Ca_{38}Mg_{24}Fe_{38}$		$\sim Fs_{35}$	Fa_{91}	│	│	│	
	H_G } Hybrids	An_5	$(Ca+Mg)_{72-79}Fe_{21-28}$				│		│	
	H_I } Hybrids	An_{46}	$Ca_{40.5}Mg_{39}Fe_{20.5}$				│		│	
	Diorite	An_{53}	$Ca_{40}Mg_{37}Fe_{23}$			┆	│		│	
	Gabbro	$An_{65.5}$	$Ca_{40}Mg_{39}Fe_{21}$	│			│			
	Cone-sheets	An_{87}	$Ca_{40}Mg_{47}Fe_{13}$	│			│			
	Eucrite	$An_{90(79)}$	$Ca_{42}Mg_{42.5}Fe_{15.5}$	│		$\sim Fa_{20}$	│			

A. THE FIRST PHASE ROCKS

3-1: EUCRITES

1. The Hólar-Skessusaeti Intrusion

Four distinct rock types are found in this intrusion, and these are, in order of consolidation:-

(a) Marginal fine-grained plagiophyric eucrite.

(b) Coarse-grained eucrite.

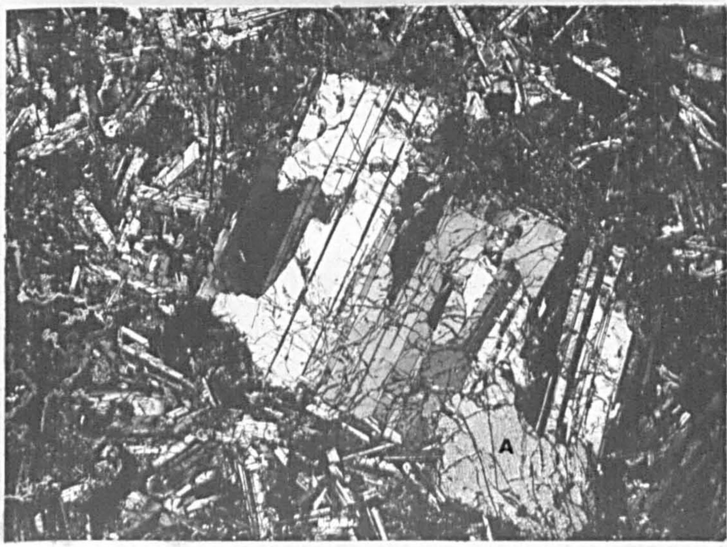
(c) Fine-grained marginal dolerite.

(d) Coarse pegmatitic gabbro, occurring as patches, stringers and veins in types 2 and 3.

(a) Marginal fine-grained eucrite (Fig. 52)

This rock forms the uppermost 9-12 m. of the intrusion and is of medium-grained dark dolerite. Plagioclase phenocrysts up to 8 mm. in length are abundant; these have near-equant habit, showing slight elongation along the c-axis, and are twinned dominantly on albite and Carlsbad laws with occasional pericline twinning. The plagioclases show pronounced zoning with a broad bytownite core area showing faint continuous normal zoning from An_{90} to An_{77} which makes up to 80 per cent of the crystal; outside this is a rim of more sodic feldspar, normally zoned with shadowy discontinuities through labradorite (about An_{56}) to a rim of andesine with high-temperature optics (see Chart 2). Although zoning is generally normal (i.e. towards more sodic rim compositions) extremely thin reversed zones were found in some crystals; these were not studied in detail but appear to be analogous to those seen in the plagioclases of the chilled Border Group rocks of the Skaergaard Intrusion (Carr 1954, Wager and Brown 1968).

Fig. 52



Marginal fine-grained eucrite from the 320 m. level in the Hólar outcrop, showing a large bytownite-anorthite phenocryst on to which is moulded a calcic augite phenocryst (A). The groundmass is composed of small labradorite laths with interstitial pigeonitic pyroxene and ore grains. Some green fibrous alteration product can be seen above the plagioclase phenocryst.

Cross-polarized light, x 15 (Specimen Vi 505).

Some of the phenocryst sections contain a central area of small tabular ferromagnesian inclusions aligned parallel to their margins, and thin zones of similar inclusions were seen in the rims of other phenocrysts. The plagioclase phenocrysts are usually not intergrown with other minerals, but the outermost, labradorite-andesine rims sometimes enclose small grains of the groundmass pyroxene. Large subhedral grains of very pale brown calcic augite up to 2 mm. in length are sometimes seen partly moulded against plagioclase phenocrysts in glomeroporphyritic clusters; these pyroxenes show no optical inhomogeneities which could be interpreted as compositional zoning and are sometimes twinned parallel to the (100) plane. One pseudomorph after olivine was found in one of the four examined sections of the rock; this is a subhedral grain of equant section 2 mm. across and is an aggregate of serpentinous material, ore and carbonate.

The matrix of the rock consists of numerous small plagioclase tablets flattened in the (010) plane which show an apparently continuous size range from 1.0 x 0.75 x 0.25 mm. down to a length of about 0.2 mm. These crystals are twinned on the same laws as the large plagioclases and the anorthite content of their cores appears to decrease pari passu with their length from bytownite (An_{77}) to sodic labradorite (An_{50}); this compositional range coincides with that of the zoned rims of the large plagioclases, and the crystals are zoned down to andesine (about An_{30}). The largest matrix crystals are taken to be microphenocrysts and the smallest to be true groundmass crystals.

Small anhedral equant grains up to about 1.0 mm. in diameter of almost colourless clinopyroxene are interstitial to the smaller plagioclases and these show a positive uniaxial interference figure and low birefringence which is taken to indicate that they are pigeonitic types similar to those first described from Icelandic basalts by Hawkes (1916a); Carmichael (1964, p. 438) noticed clinopyroxene with uniaxial to near-uniaxial optical character in the groundmasses of the Thingmúli basic lavas and suggested that it was a pigeonitic type, later confirming this identification with electron microprobe work (Carmichael 1967a). Uniaxial to near-uniaxial clinopyroxene will be referred to as pigeonite in the sequel.

The small pigeonites may be enclosed by the sodic rims of the large plagioclases, and they themselves may partly enclose the smallest groundmass plagioclases in sub-ophitic intergrowth.

A few calcium-rich clinopyroxenes were found as phenocrysts and groundmass crystals in this rock, and these have high optic axial angles ($2H_\gamma$ = 51-58°) indicative of a high calcium content.

Small acicular crystals of ore mineral are present throughout the rock and other ore crystals in the rock often show euhedral polygonal or elongated sections up to 0.7 mm. in length; the rims of these grains often form sub-ophitic intergrowths with the matrix plagioclases and may be moulded on to the large phenocryst plagioclases. The presence of moderately large euhedral grains in this chilled rock suggests that these grains are phenocrysts which have acquired later overgrowths from the quickly cooled interstitial liquid.

No apatite was found in this rock, and the final gaps in the mesh are occupied by greenish chloritic material which may represent a deuterically altered glassy residuum; small patches of ragged quartz grains were found in some of these gaps and are thought to be of hydrothermal origin.

(b) Coarse-grained eucrite (Figs. 53a and 53b)

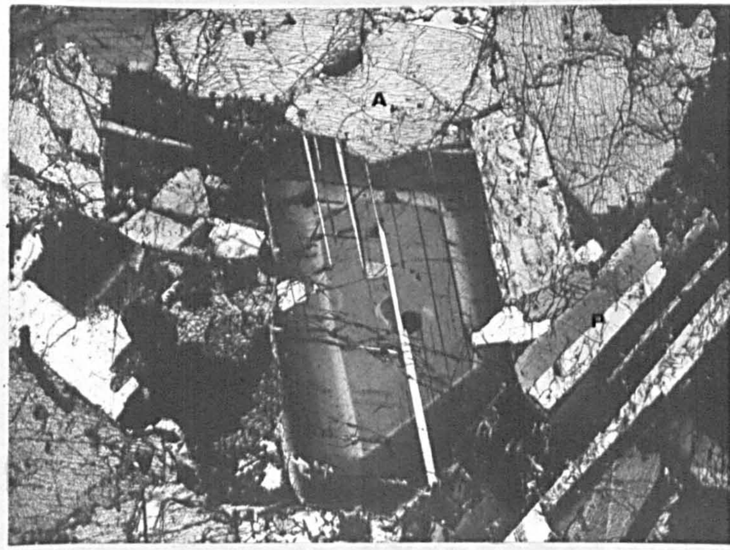
This rock forms the bulk of the intrusion and grades uniformly into the upper marginal eucrite, showing textural uniformity over a total thickness of about 150 m. The mode of this rock is:

Plagioclase phenocrysts	62.7
" microphenocrysts	7.7
Olivine phenocrysts	5.2
Clinopyroxene	19.6
Ore	1.7
Accessory minerals	0.3
Interstitial material	2.8

The large plagioclase phenocrysts seen in the upper marginal rock are abundant in this rock and show the same type of zoning as this rock with slightly more sodic rim zones (An_{30}) (see Fig. 53a).

Pseudomorphs after olivine appear to be more abundant in this rock than in the marginal eucrite (see Fig. 53b), and can be seen as pale greenish patches of fibrous material crossed by the original olivine cleavage cracks; these grains are from 2 to 7 mm. in length and have subhedral form. Olivine grains sometimes occur together with the large plagioclase phenocrysts in glomeroporphyritic clusters, indicating that they are also of early crystallization; no fresh unaltered olivine crystals were found in any part of the Hólar-Skessusaeti intrusion. The margins of some olivine grains in this rock sometimes enclose the tips of the larger matrix plagioclase crystals (An_{77} to An_{70} cores) in sub-ophitic intergrowth, indicating that olivine precipitation continued into the phase of matrix crystallization.

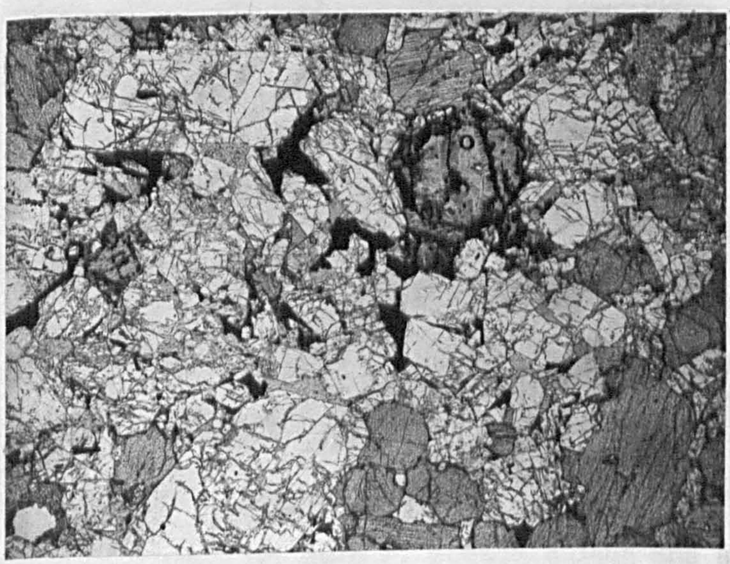
Fig. 53a



Eucrite from the 220 m. median level of the Hólar outcrop. In the centre of the field is a large zoned plagioclase phenocryst showing the characteristic bytownite core and broad labradorite andesine rim, in which some shadowy distontinuous zoning can be seen. Right of this crystal is a microphenocryst plagioclase (P) which shows a narrower sodic rim. Above the large phenocryst is a large augite phenocryst (A) which is part of an originally glomeroporphyritic cluster.

Cross-polarized light, x 15 (Specimen Vi 556).

Fig. 53b



Eucrite from the same level of the Hólar outcrop as that shown in Fig. 53a, showing the intergranular texture of the matrix, and the tabular matrix plagioclases. The ore mineral in the centre of the field shows interstitial habit, and a single large pseudomorph after olivine (O) can be seen just above the centre of the field.

Plane-polarized light, x 15 (Specimen Vi 560).

The most abundant clinopyroxene in the eucrite is a very pale-brown calcic augite ($Ca_{42}Mg_{42.5}Fe_{15.5}$; No. 1, Fig. 90) which occurs as subhedral to euhedral crystals up to 2 mm. in length which are generally interstitial to the most calcic plagioclase phenocrysts and sometimes enclose the matrix plagioclases in sub-ophitic or poikilitic intergrowths, a few large grains being associated with the large plagioclase phenocrysts in glomeroporphyritic clusters (see Fig. 53a). Many of the grains show extremely fine dark lamellae parallel to the (001) plane; these show no difference in birefringence to the host crystal, but may be lamellae of exsolved pigeonite (Brown 1957; Deer, Howie and Zussman 1965, Vol. 2, p. 130). Some augite grains show a narrow rim of homoaxial pigeonitic pyroxene with low birefringence; these rims form about 10 per cent of the width of the crystal and are often almost wholly inverted to orthopyroxene dotted with minute augite blebs. The bleb-like form of the exsolved augite indicates incomplete exsolution and these inverted pigeonites appear similar to those described from the chilled margin of the Skaergaard Intrusion (Brown 1957, pp. 530-31). Smaller anhedral equant grains of pale-brown pigeonitic pyroxene with extremely small 2V are interstitial to the phenocryst and matrix plagioclases and the larger augite crystals; the relative proportions of these two clinopyroxenes in the rock are difficult to assess. Rare euhedral prisms of orthopyroxene up to 2 mm. in length are seen in this rock; these were not seen to contain exsolved blebs of clinopyroxene and are felt to be early phenocrysts by analogy with similar types which occur in the Skaergaard Intrusion (Brown 1957).

Ilmenite is present as skeletal crystals which may range up to 15 mm. in length in some parts of the intrusion, as at the 530 m. level in the Skessusaeti outcrop; these crystals are often moulded on to plagioclase, pyroxene, olivine and apatite grains, indicating that the ore crystallization finished at a late stage in the cooling history of the eucrite (see Figs. 53b and 54).

Fig. 54

Eucrite from the 230 m. level of the Hólar outcrop showing a large ore grain of interstitial habit moulded on to a large plagioclase phenocryst, a matrix plagioclase (M), and pyroxene grains (A).
Cross-polarised light, x 15 (Specimen Vi 512).

Small rods of apatite are found throughout the rock, and these range up to 1 mm. in length, with a 20:1 length to breadth ratio; these crystals are often partly enclosed by ore grains in sub-ophitic texture.

The final remaining gaps in the crystal mesh are infilled by a turbid isotropic glassy or felsitic residuum, which has a pale brown colour due to the presence in it of minute dust-like particles.

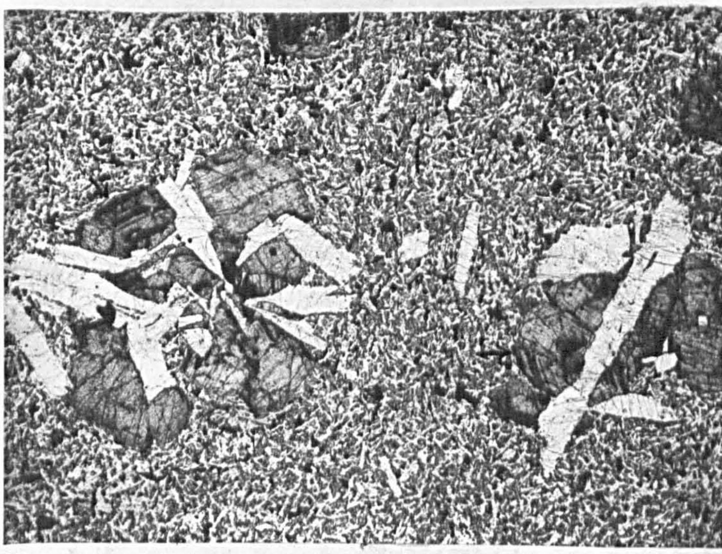
The lowest half of the main eucrite facies is of predominantly intergranular texture and true ophitic intergrowths of plagioclase and pyroxene are not abundant; the upper half of the eucrite shows a more ophitic texture, and this appears to be due to the greater abundance of flattened tabular bytownite phenocrysts in this part of the intrusion. These crystals are slightly less calcic than those in the lower eucrite and were found to have a maximum core composition of An_{80-81}, as opposed to An_{90-85} in the lower levels of the intrusion. Exsolution lamellae appear to be more abundant in the augites of these upper eucrites, but the general mineralogy is the same as that of the lower eucrites.

(c) Fine-grained marginal dolerite (Fig. 55)

This is a fine-grained dark basaltic rock of glomeroporphyritic texture which bears small phenocrysts of plagioclase and pyroxene crystals in small clusters typically about 3 mm. in diameter (see Fig. 55). The mode of this rock is:

Phenocrysts:	Plagioclase	10.9
	Clinopyroxene	4.0
Groundmass:	Plagioclase	38.0
	Clinopyroxene	36.3
	Ore	10.8

Fig. 55



Fine grained marginal dolerite from the Hólar slab outcrop, showing crystal clusters of ophitically intergrown labradorite and calcic augite set in a fine-grained intersertal matrix of more sodic labradorite and augite. Concentric zones of ore granules can be seen in the clinopyroxene grains and these are indicated by arrows.

Plane-polarized light, x 15 (Specimen Vi 575/7a).

The plagioclase phenocrysts in the crystal clusters are labradorites in a high-temperature structural state with core compositions in the range An_{67} to $An_{62.5}$ zoned continuously to rims of more sodic labradorite ($An_{58.5}$ to An_{57}). These feldspars are prismatic in form with a length to breadth ratio of 5:1 and range in length from 1 to 2 mm.; these crystals are twinned mainly on albite and Carlsbad laws, but some pericline and Baveno twins were found. A few minute bleb-like inclusions of ferromagnesian material may be present in the cores of these phenocrysts, but the crystals are otherwise clear and unclouded. These feldspars are intergrown in ophitic to sub-ophitic textures with euhedral crystals of calcic augite ($Ca_{40}Mg_{40.5}Fe_{19.5}$, No. 3, Fig. 90) which are stumpy in form with diameter 0.25-1.0 mm. and show regular octahedral sections perpendicular to the c-axis; symmetrical concentric zones of minute ore particles are developed parallel to the prism faces of these crystals, and as many as seven such zones may be seen in some augites (see Fig. 55).

The margins of these augites are sub-ophitically intergrown with the small groundmass plagioclases; these narrow marginal zones were not found to be pigeonitic. No olivine was found in this rock.

The groundmass is a fine-grained intersertal fabric of small randomly oriented plagioclase laths up to 0.2 mm. in length and showing lamellar twinning; these plagioclases are zoned from labradorite (about An_{58}) to andesine (An_{36}) and this compositional range coincides with that of the outer part of the phenocrysts. Small granules of augite bearing minute plates of ore are interstitial to these feldspars but are too small for reliable optical determination. Some of these pyroxene grains are greenish, show straight extinction and are optically negative which may indicate that they are pigeonite inverted to orthopyroxene and augite. Ore material occurs in the groundmass and appears to be of late crystallization, being moulded on to the feldspar and pyroxene grains. No gaps in the mesh were seen, and all the three primary minerals form a tightly interlocking fabric.

This rock is fresher than the eucrite parts of the intrusion, and the plagioclase and augite compositions reflect its lower content of lime and higher content of iron relative to the eucrite.

This rock is also seen in the composite vein cutting the

Skessusaeti eucrite; this vein rock is essentially similar to the rock described, but of slightly coarser grain.

(d) Pegmatitic gabbro

This rock is loosely termed pegmatitic due to its occurrence as late veins and patches in the eucrite and its coarse grain.

In thin section the rock is composed of approximately equal proportions of plagioclase, clinopyroxene and ore. The plagioclases are randomly oriented euhedral tablets flattened in the (010) plane with size commonly 2.0 x 1.0 x 0.5 mm. ranging down to as little as 0.25 mm. in length and are twinned on albite, Carlsbad and pericline laws; these grains have a virtually unzoned core of high-temperature labradorite (An_{63} to An_{60}) with a narrow continuously-zoned rim of more sodic labradorite. Pale brown augite grains up to 4 mm. in length are interstitial to the plagioclases, being often moulded on to the largest feldspars or enclosing the smaller grains in poikilitic intergrowth. Very thin lamellae parallel to (001) can be seen near the margins of most augite grains in this rock and these are thought to be exsolved pigeonite lamellae, by analogy with the augites from the Skaergaard Border Group described by Brown (1957). There is evidence that two clinopyroxenes coexisted in this rock; small areas of orthopyroxene with very fine (110) partings are sometimes seen to be filled with very thin moderately birefringent regular and continuous lamellae parallel to the (001) plane of the host crystal. These crystals are interstitial to the plagioclases and are felt to be pigeonites inverted to orthopyroxene crowded with augite lamellae (Brown 1957; Deer, Howie and Zussman 1965, Vol. 2, pp. 148-49). The presence of such inverted pigeonite grains in this rock indicates that cooling was fairly slow so that much of the augite was exsolved from the pigeonite before it finally inverted to orthopyroxene (Deer, Howie and Zussman, op. cit.).

Some augite grains are seen to be apparently intergrown with grains of euhedral orthopyroxene up to 0.5 mm. in length in this rock; these orthopyroxene grains are thought to be inverted pigeonite crystals which originally crystallized at the same time as the more calcic augite.

Other augite grains bear small scattered patches of homoaxial orthopyroxene. These orthopyroxene occurrences are felt to represent a whole range of originally pigeonitic inversion types formed by slow cooling. No olivine was found in this rock. Ilmenite occurs as grains of amoeboid form up to 4 mm. in length moulded on to both plagioclase and pyroxene grains; other small granules of ore are seen to be enclosed by the pyroxenes.

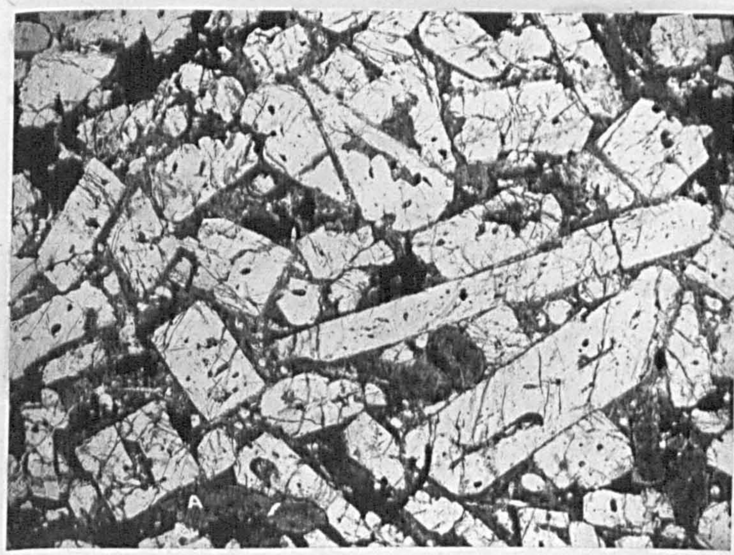
These pegmatitic gabbros are so similar in texture and mineralogy to the "wavy-pyroxene" rocks described from the Skaergaard Border Group (Wager and Deer 1939; Wager and Brown 1968) that they are possibly of similar origin. The poikilitic pyroxenes of the Skaergaard rocks are believed to be due to "growth from a liquid supersaturated for pyroxene, which occupies the interstices of the earlier plagioclase and olivine crystals. The texture of this rock indicates that plagioclase and olivine nucleated abundantly and grew to a considerable size before any pyroxene formed; then, on further loss of heat, a few pyroxene nuclei developed which grew inwards within the interstitial liquid and formed extensive poikilitic crystals having whatever orientations the original nuclei happened to have. Thus they tended to become indefinite poikilitic sheets, set perpendicular to the contact because the approximately vertical front of crystallization moved inwards as heat was lost to the country rocks across the nearby, almost vertical contact" (Wager and Brown, op. cit., pp. 121-22). These authors state that the presence of the wavy-pyroxene rock indicates that the magma was essentially stationary during the period of its formation.

This mechanism would account for the late-stage formation of the pegmatitic gabbro in the Hólar-Skessusaeti intrusion by accumulation of liquid supersaturated for pyroxene in small pockets and pools parallel to the lower margin of the intrusion. If the pegmatitic gabbro is a part of the late-stage liquid remaining from the crystallization of the eucrite it is very likely that it will be supersaturated for pyroxene; the evidence of the chilled eucrite margin shows that large amounts of calcic plagioclase and olivine crystallized out from the original eucritic liquid.

One additional rock type from the northern lower dolerite margin of the Hólar outcrop is of interest; this is a small schliere to which no chilled margins were found, and it may be related to the pegmatitic rock. This unit is hereafter referred to as the "Hólar schliere". The rock is a good example of a plagioclase orthocumulate and contains about 50 per cent of small columnar plagioclases elongated parallel to the c-axis and typically 2 x 0.5 x 0.5 mm. in size, although some individuals may reach 4 mm. in length; these crystals are twinned on albite and Carlsbad laws with minor pericline twinning (see Fig. 56). The mode of the rock is:

Acid matrix		28.4	
Phenocrysts:	Plagioclase	49.2	
	Clinopyroxene	9.9	
	Ore	12.1	(includes some interstitial ore)
	Apatite	0.4	

Fig. 56



Plagioclase orthocumulate of the Hólar schliere, showing abundant euhedral columnar labradorites with some development of skeletal form. Small prismatic augite crystals are also present (A) and some interstitial ore is seen in the upper left-hand corner of the field. The fine-grained felsitic matrix material can be seen between adjacent plagioclase crystals and also in the small cavities within these crystals.

Plane-polarized light, x 15 (Specimen Vi 575/6).

The cores of the plagioclase crystals are of almost unzoned high-temperature labradorite in the range An_{55} to An_{50}, and the narrow rims of the crystals are zoned down to andesine (An_{36}). Small cavities within the plagioclases are seen to be infilled by pale brown glassy material.

Small euhedral prismatic pale brown augite grains elongated parallel to the c-axis are also present, and may show embayed margins in section; these grains often show numerous extremely thin exsolution lamellae of pigeonite parallel to (001) as in the pegmatitic gabbro, and often show good octahedral sections. These pyroxenes may enclose small ore grains and are sometimes seen to enclose small columnar apatites. None of these pyroxenes were seen to be moulded on to the plagioclases or any of the other minerals.

The ore grains in the rock are interstitial to the feldspar and pyroxene grains; the proportion of ore in the rock is variable and ore-rich bands may be present. Numerous small euhedral apatite crystals showing columnar habit and good hexagonal sections perpendicular to the c-axis are seen in the rock; these are typically 0.5 x 0.1 x 0.1 mm. in size and are often partly or wholly enclosed by ore grains.

The matrix of the rock is a fine-grained pale brown felsitic residuum of alkali feldspar and quartz which may represent devitrified glass; this residuum is charged with small dust-like particles and minute needles of ferromagnesian material, and is similar to the final residuum already described in the eucrites.

2. The Borgarvirki Eucrite

The rock of this intrusion is almost uniform in texture throughout its outcrop with some decrease in grain size to a coarse-grained ophitic olivine dolerite near the margins (see Fig. 57a).

Scattered plagioclase phenocrysts of near equant habit with some elongation along the c-axis are found in this rock, but are not abundant; these range up to a size of about 2.0 x 1.5 x 1.0 mm. and are twinned on albite, Carlsbad and pericline laws like the Hólar-Skessusaeti plagioclases. These plagioclases have cores of calcic bytownite (An_{85}) which may contain small ferromagnesian inclusions and are surrounded by a broad rim zoned from about An_{77} to An_{50}; the zoning pattern of the rim is variable and may be continuous or discontinuous, showing several thin reversals in the latter case. The outer rims of these phenocrysts may enclose the tips of small matrix plagioclases.

The matrix plagioclases are similar in general features and composition to those of the marginal eucrite in the Hólar-Skessusaeti intrusion and appear to show a general decrease in size from 0.7 to 0.1 mm. with decrease in the anorthite content from about An_{70} to An_{40}; this trend was not assessed quantitatively. These crystals are zoned down to andesine (about An_{40}) and one small crystal of calcic andesine (An_{44}) was found to show high-temperature optics.

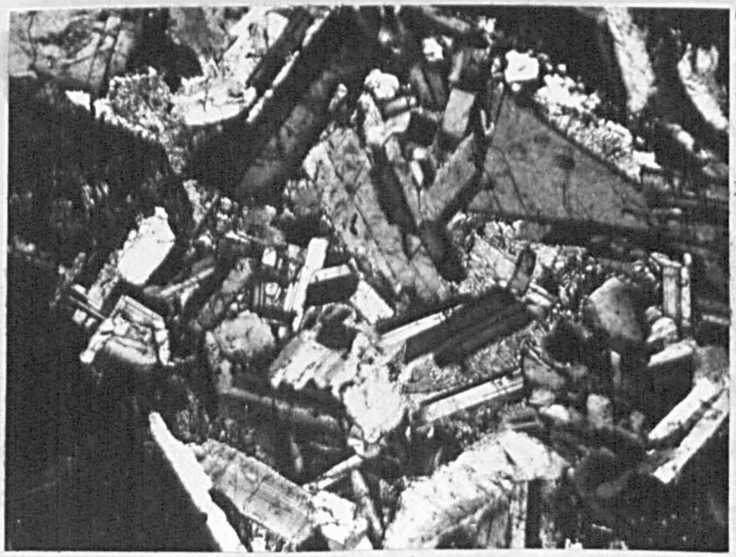
The pyroxene in this rock is a pale pink-brown augite which occurs as large crystals up to 4 x 3 mm. in size; these crystals are sometimes twinned parallel to (100) and their margins show ophitic and poikilitic

Fig. 57a

The marginal facies of the Borgarvirki eucrite, showing a large pseudomorphed olivine phenocryst (O) set in a matrix of ophitically intergrown augite and small plagioclase laths with interstitial ore of later crystallization.

Cross-polarized light, x 15 (Specimen B 10).

Fig. 57b



The main facies of the Borgarvirki eucrite, showing small labradorite and andesine plagioclases and the interstitial development of micrographic material.

Cross-polarized light x 50 (Specimen Bv).

intergrowths with single laths or clusters of the matrix plagioclases. A faint zonation parallel to the prism faces of the original augite core can be seen in some grains, and the general absence of enclosed plagioclases in this zone indicates that the intergrowths were not formed until the diameter of the augite prisms had grown to about 0.7 mm. In the dyke-like mass of similar eucritic rock which lies in the Vididalsá 3.5 km. north of this intrusion and about 120 m. below it, the augites show a more distinct columnar habit and a narrow rim of intergrowths, representing a more immature stage of pyroxene crystallization. No exsolution or inversion textures were found in these pyroxenes, and the rock appears to contain only one pyroxene; the margins of the grains were not found to have lower 2V than the cores of the grains.

Olivine is present as scattered grains pseudomorphed by greenish serpentinic material, carbonate and ore and these grains range in size from 0.5 to 3.0 mm. (see Fig. 57a). The smaller, younger phenocrysts are often seen to be enclosed in poikilitic texture by the augite grains, and may show good euhedral form with well-developed (021) faces; the phenocrysts not enclosed by pyroxene have overgrowths of later-precipitated olivine which often enclose the tips of small groundmass plagioclase laths. These overgrowths are seen over the whole size range of olivines, and indicate that olivine and augite crystallized simultaneously in this rock. These olivines are usually too highly altered for optical determination, and their composition was not determined. Similar subophitic and ophitic olivines have been described from the Shiant Isles alkali-olivine-basaltic sill, and these reach extreme rim compositions of Fa_{90} (Johnston 1953); the rims of the Borgarvirki olivines probably never reach this composition, but by analogy with the Skaergaard intrusion, the olivine crystallizing at the same time as An_{60} plagioclase will have a composition of about Fa_{40} (Wager and Deer 1939; Wager and Brown 1968). Further indication of the simultaneous precipitation of olivine and plagioclase in this rock is given by the presence of "shared" groundmass plagioclase laths enclosed at opposite ends by olivine and pyroxene.

The ilmenite grains in this rock range from euhedral platy grains partly enclosed by augite to anhedral grains moulded on to grains of plagioclase, olivine and augite; this indicates that its period of crystallization began before and ended after that of the pyroxene.

Small rods of apatite up to 1 mm. inlength with a length to breadth ratio of 25:1 occur in parallel bunches of ten or more individuals in the remaining gaps in the crystal mesh, and the final infilling to these gaps is a pale brown or pale greenish glassy residuum charged with small dust-like particles and minute crystallites. Minute needles of colourless clinopyroxene up to 0.1 mm. in length with a 20:1 length to breadth ratio are sometimes seen in this material; these are dotted with minute ore granules and are very similar in appearance to the acicular pyroxenes to be described in the acid minor intrusions of Vididalsfjall. The general texture of these final residua is extremely similar to that of the minor acid intrusions, but is of much finer grain.

An acid quartzo-feldspathic residuum was also found in the main facies of the Borgarvirki eucrite, and this shows micrographic texture (see Fig. 57b).

3-2: EARLY BASIC CONE-SHEETS

These sheets are formed of dolerite which shows great uniformity in texture within each of the three main cone-sheet types. Olivine was found to be virtually absent from these early set cone-sheets, and was only seen in one thin section.

Types 1 and 2 (Figs. 58, 59a and b)

These two types are the end members of a series in which feldsparphyric Type 1 sheets grade into aphyric Type 2 sheets by decrease in the proportion of plagioclase phenocrysts; the dolerite of the Type 2 sheets is identical in mineralogy and texture to the matrix of the Type 1 sheets.

Marginal Facies of the Sheets

Euhedral phenocrysts of plagioclase, augite and ore are seen in the Type 1 sheets up to a short distance from the contact (see Fig. 58) and the number of these crystals in the rock increases inwards from the contact; crystals with elongated habit generally lie parallel to the contacts. The plagioclase phenocrysts have bytownite cores

(An_{88} to An_{80}) and show a narrow rim zoned to more sodic plagioclase (An_{70} to An_{60}) with an outer rim of andesine (An_{36}); this rim is generally narrow and forms about 10-20 per cent of the width of the crystal. These plagioclase crystals are generally tablets of size 2 x 1 x 0.5 mm. flattened parallel to (010) and showing some elongation along the c-axis, but may be acicular crystals up to 3 mm. in length; the crystals are twinned on albite, Albite-Carlsbad, Carlsbad and pericline laws.

The clinopyroxene phenocrysts are euhedral prisms of size about 1.5 x 0.5 x 0.5 mm. sometimes twinned parallel to (100) and may show faint zoning from a pale pink-brown calcic augite core to a margin of similar appearance but low 2V which is probably pigeonitic. These pyroxenes have sharp boundaries, but their rims may enclose the tips of the small ilmenite phenocrysts. Ilmenite occurs as tabular crystals up to about 1.2 mm. in width and 0.2 mm. in thickness which may show skeletal form; these crystals have sharp outlines up to about 1.5 cm. from the contact when they show marginal intergrowth with the groundmass crystals.

These three phenocryst minerals may occur together in clusters or singly; the augite grains are moulded on to the plagioclases and the evidence indicates that plagioclase crystallized first, followed by pyroxene; the ore started to crystallize shortly before the end of pyroxene crystallization.

No olivine phenocrysts were found in the margins of these Type 1 and 2 sheets.

The groundmass of the sheet margins is often a glassy rock (now altered) charged with small ore granules which passes into finely crystalline rock bearing plagioclase microlites at about 1.5 mm. inwards from the contact. Minute pale brown granular pyroxene grains and opaque ore granules are dotted throughout this groundmass interstitial to the plagioclase microlites, which often show fluxion parallelism to the margins of the phenocrysts.

A much altered vein was found in the lower margin of one Type 1 sheet from Krossdalur; this is a yellow-brown devitrified glass bearing some plagioclase microliths and is rich in small rods of ore arranged in spherulitic or criss-cross structures. The surrounding groundmass of the rock is of similar material to that of the vein but is poorer in ore; this vein structure appears to be a late residuum of the type described from the late set cone-sheets (p.252 and Fig. 44).

Main Facies of the Sheets (Figs. 59a and b)

The margins of the sheets grade into the main facies by gradual increase in size of the groundmass plagioclase crystals to about 0.7 x 0.2 x 0.2 mm. over a distance of about 7-8 cm. from the contacts; these plagioclases have core compositions in the range An_{68} to An_{43} and they are twinned on albite, Albite-Carlsbad and Carlsbad laws. The groundmass pyroxenes increase in size to about 0.8 x 0.3 x 0.2 mm., showing euhedral to subhedral prismatic form and pale pink-brown colour. These grains are interstitial to the plagioclase laths and may enclose their tips in sub-ophitic texture; they are often uralitised with rims of a pale green amphibole (Deer, Howie and

Zussman 1965, Vol.2, p. 260). Fresher pyroxene grains can be seen to have a narrow rim of near-uniaxial pigeonitic material which appears to be optically continuous with the core of the grain; similar pigeonitic rims have been described in the Thingmúli basalt groundmass pyroxenes by Carmichael (1964, 1967a). The cores of grains in this rock were found to be of calcic augite ($Ca_{40-41}Mg_{47}Fe_{12-13}$, Nos. 15 and 16, Fig. 90), and no exsolution lamellae were found in the examined sections of these rocks. Occasional small grains of pigeonitic clinopyroxene with small 2V were found in the groundmass of the rock, but the proportion of these in the rock is difficult to assess, as they are very similar in appearance to the more calcic pyroxenes.

A few extremely small equant anhedral pseudomorphs after olivine were found in one thin section of a sheet from Krossdalur; these grains are poikilitically enclosed by the groundmass pyroxene and are thus interpreted as microphenocrysts of early precipitation.

The plagioclase phenocrysts in the main facies show rather broader sodic rims than do those in the marginal facies; these crystals are zoned down to about An_{77} from cores in the range An_{88} to An_{80}, and the broad rim is zoned from An_{77} down to as little as An_{36}. The latter part of this zoning range (An_{77} to An_{36}) is the same as that shown by the groundmass plagioclases, and is of high-temperature structural type, showing shadowy discontinuities in the zoning.

The ilmenite in this rock shows interstitial habit due to the moulding of the later marginal parts of the phenocrysts on to the plagioclase and pyroxene grains; some grains show sub-ophitic intergrowth with the groundmass plagioclase laths.

Apatite is seen as short euhedral rods usually less than 0.5 mm. in length, but which sometimes reach lengths of 2 mm. and show a length to breadth ratio of 20-40:1; these rods are usually found only in the final gaps in the crystal mesh which are filled with a devitrified and greenish residuum bearing small euhedral laths of andesine (about An_{40} to An_{36}). The abundance of this residuum in some sheets is felt to evidence their rapid consolidation, as shown by the mode of a Type 2 sheet from Krossdalur:

Plagioclase	49.5
Clinopyroxene	26.2
Olivine	0.4
Ore	10.2
Interstitial material	14.8

Eucrite and Gabbro Inclusions in Type 1 and 2 Sheets (Fig. 59b)

Inclusions of coarse-grained basic rocks were found in some of the lower-level Type 1 and 2 cone-sheets (marked "Ei" on Map 2), and some of these inclusions are in the form of loose crystal aggregates floating in the cone-sheet dolerite with their interstices filled by this material. These inclusions show different stages of crystallization which can be broadly related to the crystallization and differentiation sequence seen in the surface outcrops of eucrite and gabbro. In three of the four thin sections examined the inclusions are of

Fig. 58

Lower contact of a Type 1 early set cone-sheet from the east side of Skessusaeti. Small phenocrysts of plagioclase ((P), some showing lath sections, and augite (A) can be seen close to the originally glassy lower contact of the sheet; this contact lies against fine-grained country rock basalt in the bottom left corner of the picture. Small opaque ore microphenocrysts are also present, and a small acid patch is seen at S.

Plane-polarized light (Specimen Vi 546/1).

eucrite composed dominantly of calcic plagioclase and clinopyroxene. The plagioclase crystals account for about 70 per cent of the volume of these inclusions and are of similar euhedral tabular to equant form to the phenocrysts seen in the Hólar-Skessusaeti eucrite; the feldspars are up to 4 mm. in length, showing twinning on the same laws as the Hólar-Skessusaeti plagioclases, but a more limited range of zoning. The cores of these crystals are of bytownite in the range An_{86} to An_{83} and are zoned to margins of labradorite (about An_{68}) with high-temperature optics; smaller phenocrysts with core compositions of An_{77} are also present, as in the surface outcrops. This range of zoning indicates that these plagioclases were removed from their parent liquid before they could form the broad labradorite-andesine part of the rim seen in the Hólar-Skessusaeti eucrites.

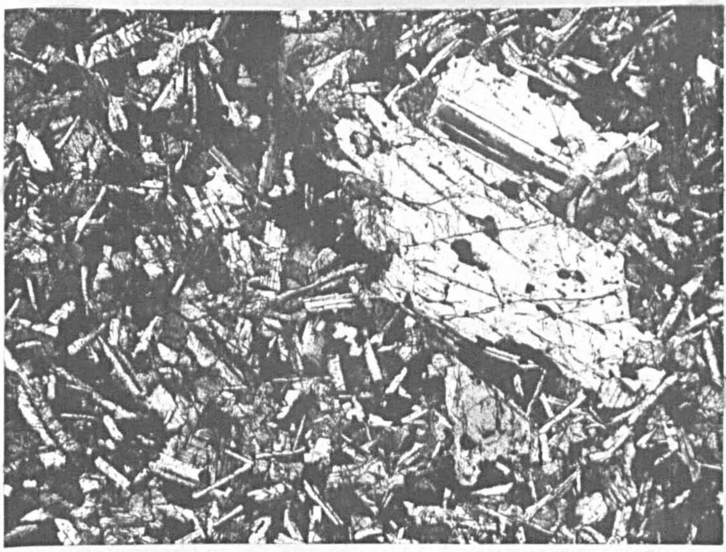
The clinopyroxene in the inclusions is a very pale brown type similar in appearance to that seen in the surface eucrites and, by analogy, is probably a calcic augite; these grains are up to 8 mm. in length, being largely interstitial to the large bytownites and enclosing the smaller plagioclase phenocrysts in ophitic and poikilitic textures; A pseudomorphed olivine phenocryst was seen in one specimen; this also is enclosed by pyroxene. Two of the inclusions contain no ore and the plagioclases in these rocks are zoned from An_{86} to about An_{68}. Plagioclases in this compositional range are usually seen to be accompanied by ore grains in the chilled margin of the Hólar-Skessusaeti eucrite; this may indicate that the component crystals of these inclusions accumulated in some part of a differentiating eucrite liquid which did not precipitate ore.

The third eucrite inclusion bears small ore grains up to 0.5 mm. in length which are taken to represent the early stages of ore crystallization. The pyroxene grains in this rock sometimes show a very narrow rim of near-uniaxial clinopyroxene which may be pigeonite; these rims enclose the tips of groundmass plagioclase laths in the adjoining host dolerite in sub-ophitic intergrowth and are felt to represent overgrowths of pigeonitic pyroxene precipitated from the host dolerite liquid. Some of the clinopyroxene grains in this and all inclusions examined show a slightly uneven extinction which is possibly not zoning, but a strain effect due to transport of the crystals before they were fully consolidated; the writer has noticed a similar feature in the augites of alkali-olivine-dolerite sills from the Hebrides.

The remaining inclusion examined is a gabbro bearing large euhedral tablets of almost unzoned labradorite with cores in the range $An_{69.5}$ to $An_{65.5}$; these crystals are typically 4 x 2 x 1 mm. in size, and are twinned on albite, Carlsbad and pericline laws (see Fig. 59b). The cores of these crystals contain a few inclusions of ferromagnesian material.

The clinopyroxene is the pale pink-brown type commonly seen in the gabbros at Hôlar, Skessusaeti, Urdarfell and Steinsvad and, by analogy with these rocks, it is taken to be a calcic augite; these augites are large tabular crystals about 4 x 3 x 3 mm. in size and show euhedral prism faces where their margins do not abut against plagioclase crystals. A narrow rim of near-uniaxial pigeonitic pyroxene is found at those crystal margins in contact with the cone-sheet dolerite; these margins can be seen in places to be in continuity with the groundmass pyroxene and may enclose small groundmass ore and plagioclase grains. Large ore grains up to 4 mm. in length were found in this inclusion; these are moulded on to the plagioclase and pyroxene grains, indicating that they finished crystallization at a later stage than these minerals.

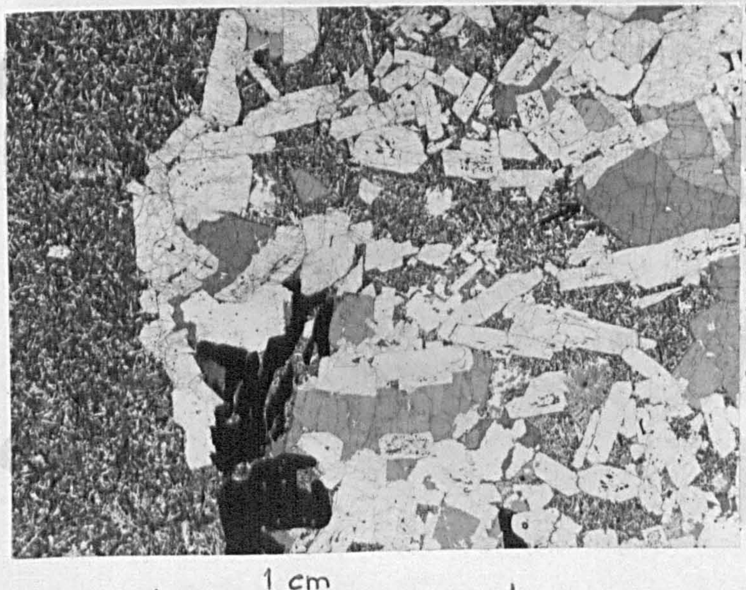
Fig. 59a



Main facies of Type 1 early set cone-sheet from the 600 m. level on the Sandfell ridge, showing a large bytownite phenocryst zoned to andesine at the margins, set in an intergranular to sub-ophitic groundmass of augite and labradorite with interstitial ore. The groundmass texture is identical with that of the Type 2 sheets.

Cross-polarized light, x 15 (Specimen Vi 60).

Fig. 59b



Gabbro inclusion from a Type 1 early set basic cone-sheet in the Krossdalur stream, showing the partial lack of cohesion between the crystals of the gabbro and the way in which these crystals are suspended in the cone sheet matrix material. A pigeonitic rim to a calcic augite is indicated by an arrow.

Ordinary light (Specimen Vi 94).

The general texture and mineralogy of this gabbro inclusion is similar to that of the pegmatitic gabbros seen in the Hólar-Skessusaeti intrusion and the Urdarfell and Steinsvad gabbros.

No apatite or glassy residual material was found in these inclusions, and the inclusions are taken to represent loose crystal aggregates of cumulus minerals entrained during the passage of the cone-sheet magma through large unconsolidated masses of basic material in depth beneath Vididalsfjall. No exsolution lamellae were found in any of the pyroxenes in these inclusions.

Type 3

These sheets are of extremely fine-grained basaltic material throughout, and all the examples examined were highly altered, so that accurate determination of the groundmass constituents is difficult. The sheets can be distinguished in thin section from those of Types 1 and 2 by their fine grain and high carbonate content.

Most of these sheets bear euhedral plagioclase phenocrysts of tabular form up to 4.5 x 2 x 1 mm. in size which make up to 40 per cent of the rock by volume; these crystals are flattened parallel to the (010) plane and are twinned on albite and Carlsbad laws with minor pericline twinning. The largest feldspars have bytownite cores with a composition of An_{85} to An_{80}, but some microphenocrysts with core compositions of An_{70} were found and these showed high-temperature optics. The transition from the calcic core to the more sodic rim zones is not abrupt as in the phenocrysts of the eucrites and Type 1 and 2 sheets, but is of more continuous character; in addition, the sodic rims of these phenocrysts are extremely narrow and were not often seen to enclose groundmass crystals. Many of the plagioclase phenocrysts show skeletal form with small cavities infilled by glassy or holocrystalline groundmass material; these features are seen in crystals of all sizes.

Rare phenocrysts of altered augite were found; these are very pale brown in colour, forming euhedral prisms up to 1.5 x 1.0 x 1.0 mm. in size, and sometimes enclose the smaller plagioclase phenocrysts in ophitic to sub-ophitic textures. The edges of these crystals are sharp but a very narrow rim zone can be seen in some grains to enclose the tips of minute groundmass feldspars; no uniaxial pigeonitic rims or indications of zoning were seen in these pyroxenes, but it seems likely (by analogy with the Type 1 and 2 sheets) that pigeonite may be present.

The groundmass of the rock is an extremely fine-grained intersertal fabric of randomly oriented labradorite laths (about An_{69}) up to 0.3 mm. in length which are zoned to about An_{30}, and interstitial pyroxene on to which ore is moulded. The pyroxenes are completely replaced by highly birefringent carbonate; a similar replacement is seen round the margins of the pigeonite grains in the chilled upper margin of the Hólar-Skessusaeti eucrite and the carbonate grains in the Type 3 sheets are thus felt to represent replaced pigeonite crystals. The ore grains may show subhedral quadrilateral or elongated sections, but are usually interstitial to the feldspar and pyroxene. Small patches of greenish chloritic interstitial material fill the remaining gaps in the mesh, and these may represent an originally glassy residuum, as in the Type 1 and 2 sheets and the eucrites.

3-3: TWO SMALL GABBRO INTRUSIONS AT THE PERIPHERY OF THE CONE-SHEET SWARM

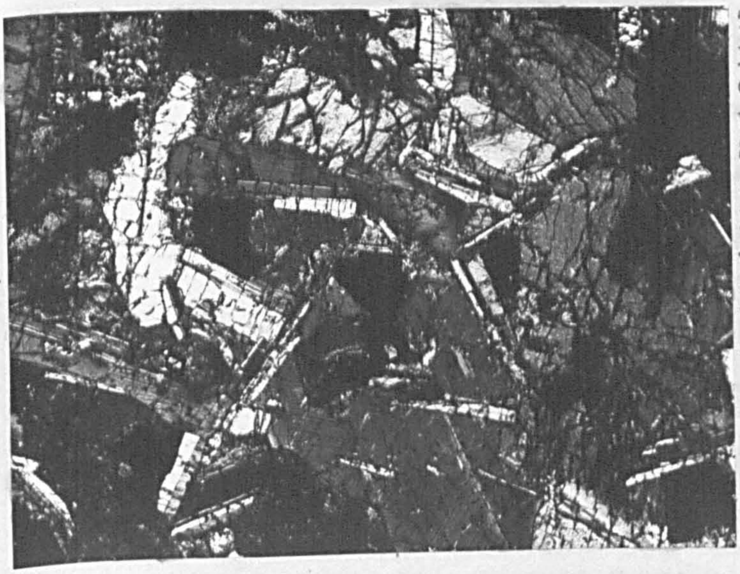
1. The Steinsvad Gabbro Intrusion

This gabbro has almost identical mineralogy to the Urdarfell gabbro, but shows much smaller grain size and more abundant poikilitic intergrowths of pyroxene and plagioclase than the Urdarfell rock (see Fig. 60).

The plagioclase in this rock occurs as almost euhedral prismatic tablets flattened parallel to (010) which are up to 4 x 2 x 1 mm. in size and are twinned on albite, Albite-Carlsbad, Carlsbad and pericline laws; these crystals show strong continuous zoning from cores of high-temperature labradorite ($An_{62.5}$) to margins of sodic andesine (An_{34}). There is considerable variation in the size of the plagioclases in the rock, and an apparently continuous range of sizes down to lengths of about 0.5 mm. was found in the rock, the smaller crystals having the more sodic core compositions.

The clinopyroxene in this rock is a pale pink-brown calcic augite whose composition was determined as $Ca_{39.5}Mg_{38.5}Fe_{22}$ (No. 7, Fig. 90); this mineral occurs as anhedral grains of more or less equant form up to 3 mm. in length which are interstitial to the plagioclase crystals, enclosing the tips of the larger crystals in sub-ophitic intergrowth and often enclosing the smallest crystals in poikilophitic intergrowth (see Fig. 60).

Fig. 60



The Steinsvad gabbro, showing prismatic plagioclase crystals of different sizes enclosed partly or wholly by augite (dark grey). Scattered subhedral ore grains are seen to be interstitial to both plagioclase and pyroxene crystals. A patch of pale green chloritic interstitial material is seen in the lower right-hand corner of the field.

Cross-polarized light, x 15 (Specimen Vi 2).

The augite crystals were often found to be twinned parallel to (100), but very few exsolution lamellae were found in these crystals; a few faint striations parallel to (001) were found in some crystals and these may be of exsolved pigeonite.

Opaque ore occurs in the rock as large euhedral polygonal sections up to about 2 x 1.5 mm. in area which may show skeletal form and are interstitial to the plagioclase and pyroxene, often enclosing the smallest plagioclase laths in poikilophitic intergrowths; this is taken to indicate that ore was of late crystallization in this rock.

The remaining gaps in the fabric are occupied by aggregates of fibrous green chloritic interstitial material which may represent an originally glassy residuum similar to that found in the Borgarvirki eucrite; this material was not found to show any regularity of form which might suggest that it formed pseudomorphs after olivine. A few of the plagioclase crystals were found to have very narrow discontinuous mantles of extremely fine-fret graphic quartz and alkali feldspar; these growths were never found to form entire mantles to the crystals and are interpreted as a final acid residuum which solidified more slowly than the glassy residuum.

Some small apatite rods up to about 0.4 mm. in length with a length to breadth ratio of about 15:1 were found in the green chloritic areas; these are commonly found in the glassy acid residua of the other eucrite and gabbro intrusions in the area.

Carbonate was found to form abundant ragged grains in the gaps in the fabric of this rock; this is often associated with brassy sulphide ore in veins and is felt to be of secondary origin. The whole rock shows evidence of having been hydrothermally altered, the pyroxenes showing some alteration to green chloritic material along cleavage cracks and the feldspars are often partially replaced by carbonate and cut by thin stringers of zeolitic material.

2. The Hnjúkur Gabbro Intrusion

This gabbro is the only gabbro in the Vididalur - Vatnsdalur area found to bear olivine and this distinguishes it from the olivine-free gabbros of Hólar-Skessusaeti, Urdarfell, Selfell, and Steinsvad; the presence of olivine makes the Hnjúkur gabbro similar to the basic rocks of the Second Phase of the intrusive sequence.

The Outer Dolerite

This rock is a very fresh medium coarse dolerite bearing randomly oriented plagioclase crystals which range from small euhedral tablets 1 mm. in length down to small laths about 0.1 mm. in length. These crystals show twinning on albite and Carlsbad laws, and the larger crystals are zoned from cores of high-temperature labradorite (An_{67}) to margins of andesine (An_{40}).

The clinopyroxene in this rock is a pale pink calcic type which forms anhedral equant grains up to about 1 mm. in size which enclose the feldspar laths in well-developed poikilophitic intergrowths which are very uniformly developed and make up the main units of the fabric; the margins of some of these augite grains were found to show near-uniaxial interference figures, and are taken to be of pigeonitic clinopyroxene. No obvious colour zoning or other optical discontinuity was found between these pigeonitic rims and the cores of the pyroxene crystals.

Small anhedral olivine grains up to about 0.7 mm. in length were found in this rock; these are interstitial to the plagioclase crystals, often forming sub-ophitic intergrowths with them, and are enclosed by the pyroxene crystals, indicating that they formed slightly before the pyroxene. These olivine crystals are often altered to green serpentinous material, and their composition was not determined.

The opaque ore in this rock forms small irregularly-shaped grains which are moulded on to crystals of plagioclase, pyroxene and ore, and enclose the smallest plagioclase grains in poikilophitic intergrowths; this indicates that the ore crystallized at a late stage in the cooling history of the rock.

The remaining gaps in the crystal mesh were found to be infilled by a colourless isotropic glassy material which sometimes shows a dusty appearance due to the presence of small ore particles and this material may bear small euhedral apatite rods; the glassy material was often found to be altered to green chloritic material and is very similar to the final residua observed in other basic intrusive rocks in the Vididalur-Vatnsdalur area. A few small spherical vesicles less than 1 mm. in diameter in the rock were found to be lined with this altered greenish material and infilled by carbonate.

The general texture and mineralogy of this rock is very similar to that of the widely-distributed olivine-tholeiite characteristic of the minor intrusions of the Second Phase of the intrusive sequence.

The Gabbro Core

(a) Fine-grained marginal facies. This rock is a fine-grained fabric of randomly-oriented plagioclase laths of length 0.5-1.0 mm. with small interstitial granules of augite and ore; this groundmass augite was found to be pigeonitic.

A few glomeroporphyritic clusters of large tabular plagioclase crystals were found in this rock; these crystals are up to about 7 mm. in length and are strongly zoned from labradorite cores to andesine rims. This zoning is normal but several tens of very thin shadowy discontinuities were seen in all the crystals examined, and these give the crystals a very distinctive appearance. Small rounded crystals of magnesian olivine up to about 0.5 mm. in size are enclosed by the portions of the plagioclase crystals with composition more sodic than about An_{60}; no augite crystals were found to be present in these crystal clusters.

Parts of the largely uniform intersertal groundmass of this rock were found to pass continuously into small patches of slightly coarser-grained rock with poikilophitic augite grains exactly similar in texture to those seen in the outer dolerite, and these may be late-stage pegmatitic patches. Similar patches have been found in Icelandic olivine-basalt lavas (Walker 1959) and have been observed by the writer in some of the Vididalur-Vatnsdalur olivine-tholeiite lavas. One of these patches in the Hnjúkur rock was seen to surround one of the phenocryst clusters.

(b) Coarse-grained main facies. The mode of this rock is:

Plagioclase	49.5
Olivine	1.4
Clinopyroxene	29.6
Ore	6.4
Interstitial material	13.1

This rock is markedly coarser in grain than the marginal facies and large euhedral tabular plagioclase crystals with similar discontinuous zoning to those seen in the marginal facies make up about half of the rock by volume; these crystals were found to be twinned on albite, Albite-Carlsbad and pericline laws, and to range up to 9 x 4 x 2 mm. in size. The cores of these feldspar crystals are of high-temperature labradorite (An_{70} to An_{55}) and were found to be zoned to rims of andesine (An_{40}); the more sodic core compositions are found in the small plagioclase crystals and these range down to about 0.5 mm. in size. The similarity of these large main facies plagioclase crystals to the phenocrysts in the marginal facies is thought to indicate that the main facies plagioclase crystals are cumulus crystals.

Clinopyroxene occurs in this rock as large subhedral crystals up to about 3.5 mm. in length which show some flattening parallel to (100); this is well seen in euhedral sections perpendicular to the c-axis. The pyroxene is of a pale pink-brown colour, and its composition was determined as $Ca_{38}Mg_{38.5}Fe_{23.5}$ (No. 8, Fig. 90); this value is very similar to that obtained for the Urdarfell and Steinsvad gabbro augites, and is also similar to values obtained for the late set cone-sheets of the Second Phase of the intrusive sequence. The augite is interstitial to the plagioclase phenocrysts.

A few very thin exsolution lamellae parallel to (001) were found in some of these augite crystals, but these were not abundantly developed, and they possibly represent exsolved pigeonite. No marginal rims of pigeonite were found to these main facies augite crystals.

A few pseudomorphs of serpentinous material after small rounded olivine crystals up to 1.5 x 1.0 mm. in size were found to be associated with the plagioclase phenocrysts and as in the marginal facies of the gabbro these were found to be enclosed by the outermost zones of the feldspars; some of the olivine crystals were found to be enclosed poikilitically by augite grains and they are believed to represent a second cumulus phase.

Opaque ore grains occur in the gabbro and a few of the smaller grains were found to be enclosed poikilitically by augite crystals, which indicates that ore crystallization began before that of pyroxene in this rock. Most of the ore grains in the rock are between 2.0 and 3.5 mm. in length and show subhedral skeletal form which may be more or less equant; these grains are often moulded on to the pyroxene and larger feldspar crystals in the rocks. Some of the grains were found to enclose the smallest plagioclase crystals, and this indicates that ore crystallization finished towards the end of the cooling history of the gabbro.

The final gaps in the crystal mesh are occupied by an acid residuum of variable character which may be isotropic and glassy or of fine-grained felsitic material; both types were found to occur within the same thin section and both were found to bear small euhedral rods of apatite up to 1 mm. in length. The felsitic type was found to consist of minute ragged grains of quartz and alkali feldspar, or of the same two minerals intergrown in an extremely fine-fret graphic texture; small single-crystal quartz paramorphs after platy tridymite grains were found in parts of this acid material and these show lath-sections with length to breadth ratio about 20:1. The glassy interstitial material was sometimes found to be altered to pale green chloritic material in similar fashion to the glassy residua found in the Borgarvirki and Steinsvad gabbros. As in the early set cone-sheets, the abundance of this fine-grained acid residuum is felt to be the result of rapid cooling in a high-level environment.

3-4: ACID MINOR INTRUSIONS OF THE CENTRAL ZONE

1. The Dalsá-Urdarfell Felsite Intrusion

(a) The Main Facies

The Dalsá Outcrop (Fig. 61). This body is of fine-grained holocrystalline feldsparphyric felsite which bears occasional phenocrysts of clinopyroxene and ore and shows little variation in texture.

The mode of this rock is:

Phenocrysts:	Plagioclase	3.2	
	Clinopyroxene	tr	
	Ore	0.3	
Groundmass:	Quartz nests	10.6	(includes some alkali feldspar)
	Quartz-alkali feldspar matrix	85.9	

The feldspar phenocrysts are mostly euhedral elongated crystals with clear cores of high-temperature andesine (An_{32}) surrounded by broad rims of oligoclase in the range An_{24} to An_{20}; these rims abruptly succeed the more calcic cores and may make up to 25 per cent of the crystal width. The crystals show lath and stumpy tabular or rhomboidal sections with maximum lengths of 1.5 mm. (see Fig. 61) and were found to be twinned on albite and Carlsbad laws, with occasional pericline twins; twinning is not strongly developed and may be absent in some crystals. A few crystals showed some development of skeletal habit, having narrow voids parallel to the c-axis infilled by matrix material. A large number of crystals have embayed margins at which a narrow turbid zone was seen; this may be due to resorption and reaction with the liquid phase. These turbid margins were seen to be in optical continuity with the groundmass feldspar and they show extremely fine shadowy twin lamellae, which is taken to suggest that they have a composition near that of anorthoclase.

Most of the non-turbid feldspar phenocrysts examined showed clear regular margins with a narrow apparently continuous overgrowth of slightly turbid feldspar in continuity with the groundmass feldspar.

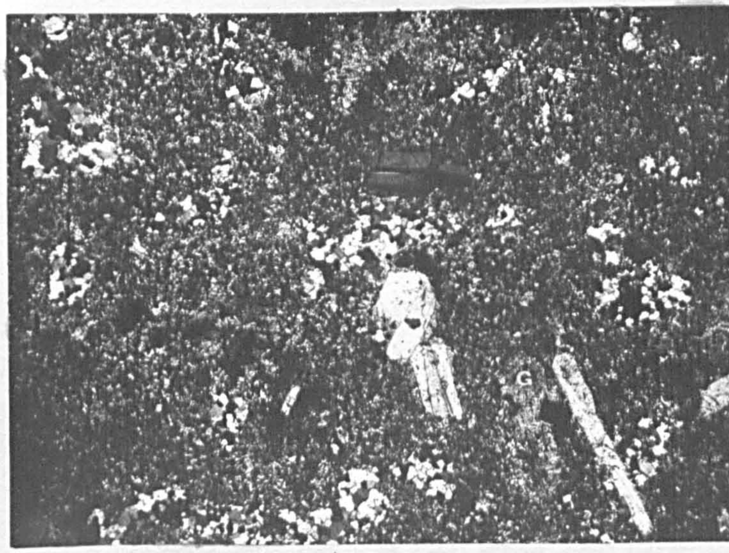
A few acicular phenocrysts up to 1 mm. inlength of pale green clinopyroxene were found in this rock; these are studded with small opaque ore grains and are felt to be ferroaugites by analogy with the pyroxenes seen in other similar rocks in Vididalsfjall; these crystals were found to have high optic axial angles ($2H_\gamma$ = 55-60°) which indicates a hedenbergitic composition.

Small opaque ore phenocrysts were found scattered throughout the rock; these are typically of euhedral to subhedral square form up to 0.1 mm. in size, and are taken to be of early precipitation, as they are sometimes enclosed by pyroxene phenocrysts.

The groundmass of the felsite is a pale-coloured "patchwork" fabric of ragged turbid alkali feldspar grains showing extremely fine twin lamellae which are felt to indicate that it is a perthitic anorthoclase type; these grains are often seen to be intergrown with minute quartz grains in ragged intergrowths which may show extremely fine-grained graphic texture.

The groundmass silica mineral may occur as thin elongated sections up to 0.2 mm. in length pseudomorphed by strings of quartz blebs; these laths can sometimes be seen to pass into equant platy crystals with ragged outlines which may be of tridymite, now inverted to quartz, by analogy with similar textures described from acid rocks in eastern Iceland by Hawkes (1916b) and Walker (1959). Similar inverted tridymites have been described from Hebridean Tertiary acid rocks by

Fig. 61



Felsite from the Dalsá outcrop, showing andesine-oligoclase plagioclase phenocrysts set in a fine-grained quartzo-feldspathic matrix which may show a crude graphic texture due to intergrowth of quartz and alkali feldspar as at G. Patches of equant quartz grains (white) of coarser grain than the groundmass quartzes can be seen scattered throughout the rock.

Cross-polarized light, x 15 (Specimen Vi 39).

Wager et al. (1953) and Skelhorn (1962); Skelhorn (op. cit.) suggests that the formation of tridymite in a Mull composite sheet formed at 430 atmospheres and a probable maximum depth of 1500 m. below the top of the basalt lava pile. Brown (1963) has estimated that the Coire Uaigneich granophyre of Skye which bears inverted tridymite was emplaced beneath a cover of about 1000 m. of basalt lava flows; the Dalsá-Urdarfell felsite is believed to have formed similarly beneath about 230 m. of basalt lava flows. The intrusion lies about 58 m. beneath the base of the BFB lava group outcrop on Urdarfell, and this group lies at about 165 m. below the base of the Hvammurtuff seen on Krossdalskúla which is taken to represent the possible top of the lava pile at the time of intrusion of the felsite.

Minute granules of pale green pyroxene and opaque ore occur in the groundmass of the felsite together with small rods of apatite and zircon.

Quartz is also seen in this rock as small clear equant grains up to 0.3 mm. in diameter forming small clusters up to 4 x 1 mm. in size together with grains of untwinned slightly turbid alkali feldspar. Occasional small anhedral fluorite crystals showing octahedral cleavages intersecting at 60° and 120° were found in these patches; these show a faint purple colour and are isotropic. Small grains of epidote, calcite, ore, zircon and rare fluorite also occur in these patches, and the material forming the clusters may have been derived from the later MU granophyre intrusion.

Part of the Dalsá rock shows breccia texture (see p.188); the main part of the outcrop shows no difference in texture from those described above but small ore-rich matrix zones can be seen to separate the angular breccia blocks. These matrix zones have sharp boundaries, and often cut across feldspar phenocrysts.

<u>The Urdarfell Outcrop</u>. The felsite in this outcrop shows the same general textural features as the Dalsá rock, bearing similar plagioclase phenocrysts of andesine zoned to oligoclase, and ore; small pale green clinopyroxene phenocrysts appear to be more abundant in this rock than in the Dalsá rock and these show slightly rounded subhedral outlines. Phenocrysts of all three minerals may occur together in loose clusters.

The groundmass shows some flow texture in which the feldspar occurs as elongated ragged grains together with thin tridymite pseudomorphs showing elongated sections; both these minerals show flow parallelism which may be further indicated by the stringing together of the minute groundmass ore blebs. The flow bands can be seen to curve round the phenocrysts, which may be slightly crushed and broken. Patches of quartz similar to those in the Dalsá rock also occur in the Urdarfell rock. Although no vesicles were found in this rock, the more prevalent flow banding and slightly finer grain size are taken to be due to its higher level of intrusion relative to the Dalsá outcrop.

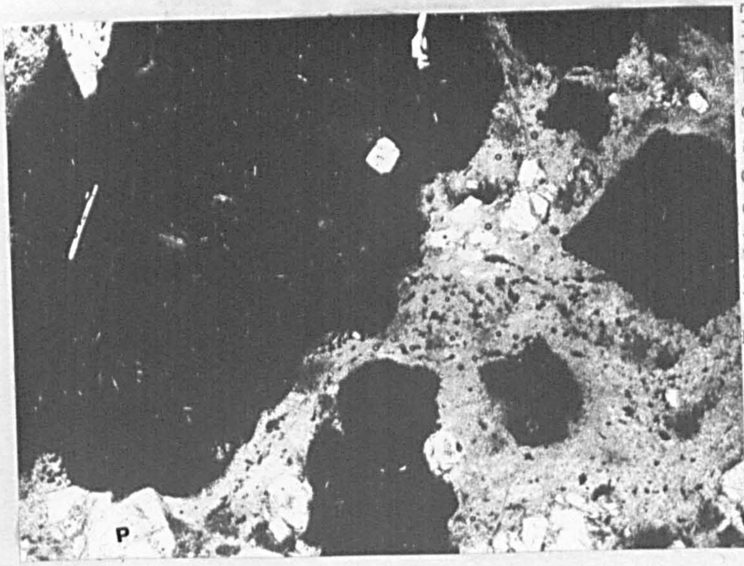
(b) The Marginal Facies

This rock shows much finer grain than the main facies of the felsite, and although it has a more vitreous appearance than this rock it was never found to be of pitchstone type; the groundmass is an extremely fine-grained equigranular fabric of alkali feldspar and quartz grains which may represent a devitrified rhyolite.

The phenocrysts in this rock are of high-temperature andesine (An_{32}) zoned to oligoclase (An_{20}), pale green clinopyroxene and opaque ore; a few feldspar phenocrysts with very fine lamellar twinning, and almost equidimensional habit, were found to have $2V_{\alpha} = 56^{\circ}$; this is taken to indicate that they are anorthbclases (see p. 491).

The rock bears about 40 per cent by volume of basic inclusions, which have been described on pages 192-95 (see Fig. 62); similar inclusions are known from other Icelandic acid rocks (Carmichael 1960b; Walker 1966a), and have been described from the margins of the Loch Bá felsite ring-dyke of Mull (Bailey et al., 1924).

Fig. 62



The upper marginal facies of the Dalsá-Urdarfell felsite on northern Urdarfell, showing inclusions of dark fine-grained basic material set in the light-coloured matrix of the felsite. A few phenocrysts of andesine and hedenbergitic pyroxene can be seen in the felsite, and the crenulate margins of the basic material suggest that this material was mobile at the time of its incorporation by the felsite. One of these basic inclusions is partly moulded on to an andesine phenocryst (P) in the felsite.

Plane-polarized light, x 15 (Specimen Vi 70).

2. The Raudkollur Felsite Intrusion

This rock is feldsparphyric, bearing about 19 per cent by volume of feldspar phenocrysts, and is very light in colour. The mode of the rock is:

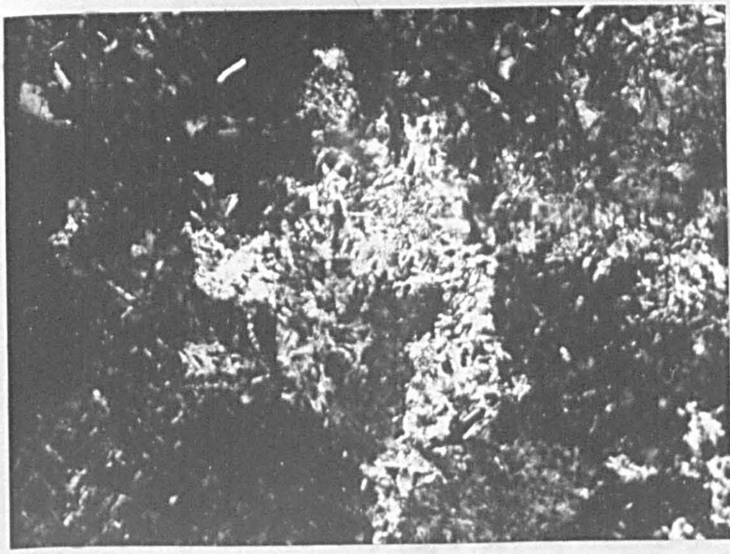
Phenocrysts:	Plagioclase	18.9
	Ore	tr
	Ferromagnesian silicates	0.2
Matrix		80.9

The feldspar phenocrysts show lath, tablet and rhomb sections of greatest length about 2 mm. and these are twinned prominently on albite and Carlsbad laws. These crystals show some normal continuous zoning which may be oscillatory and the total range in composition was found to be from cores of oligoclase (An_{22}) to margins of about An_{11}. The margins of some of the more sodic phenocrysts show very fine twin lamellae parallel to (010) which are just visible under high-power magnification, and these are thought to be of ternary feldspar in the anorthoclase field, by analogy with similar feldspars described by MacKenzie and Smith (1956), Carmichael (1960a), and Muir (1962); feldspar phenocrysts with textures suggestive of anorthoclase have been found in felsites associated with the Slaufrudal stock in eastern Iceland by Beswick (1965).

The only other phenocrysts found in the felsite were small elongated ore grains up to 0.6 mm. in length showing ragged outlines.

The groundmass of the rock is a fine-grained patchwork fabric of alkali feldspar and thin platy pseudomorphs of quartz after tridymite (see Fig. 63). These pseudomorphs are up to 0.4 mm. in length with a breadth to thickness ratio often reaching 20:1 and are commonly made of a single quartz crystal which shows extinction oblique to the lath section of the original tridymite crystal; similar oblique extinction in single crystal quartz pseudomorphs after tridymite has been described by Ray (1947), Wager et al. (1953) and Skelhorn (1962), and shows that the optic axis of the quartz is not perpendicular to the former basal pinacoids of the tridymite. Many of the pseudomorphs show criss-cross structure in thin section and are set in ragged equant grains of quartz up to 0.5 mm. in width.

Fig. 63



The quartzo-feldspathic matrix of the Raudkollur felsite, showing the patchwork texture of the rock. Small elongated sections of quartz paramorphs after platy tridymite crystals can be seen in "criss-cross" texture in the white patch in the centre of the field.

Cross-polarized light, x 100 (Specimen Vi 33).

Small ore grains can be seen scattered throughout the groundmass, together with minute needles of apatite and zircon which may form small stellate clusters. Occasional small cavities up to 1 mm. across in the groundmass are seen to be lined by wedge-shaped tridymite crystals which may show twinning; the centres of these cavities are infilled by clear equant quartz grains up to 0.4 mm. in width which may contain small euhedral rods of pink-brown pleochroic zircon up to 0.1 mm. in length. A few small pale pink columnar sphene crystals with euhedral square cross-sections up to 0.25 mm. in length are also present in the groundmass.

The marginal sheet-like portions of the Raudkollur intrusion are of rhyolitic rock similar to that of the main part of the intrusion, but cavities infilled by quartz are more abundant, making up about 8 per cent of the rock by volume. Some spherulites up to 1 mm. in diameter occur in this rock and these occur singly or in layers, giving the rock a banded appearance; a few spherulites were seen to surround feldspar phenocrysts.

Clusters of euhedral feldspars and pseudomorphs after ferro-magnesian phenocrysts similar to those seen in the main facies occur in this rock; these pseudomorphs consist of chlorite, epidote, carbonate and ore. Small areas of clear quartz inset with small euhedral laths of alkali feldspar up to 0.2 mm. in length were seen to infill the gaps at the edges of some phenocryst clusters, but no quartz phenocrysts were found in this rock.

3. Intrusions Related to the Raudkollur Intrusion

(a) The 50-degree Sheet

This intrusion shows similar mineralogy to the main intrusion, but contains phenocrysts of clinopyroxene and olivine in addition to phenocrysts of feldspar and ore; this is one of the few occurrences of olivine in acid intrusive rocks found in the area during the present study.

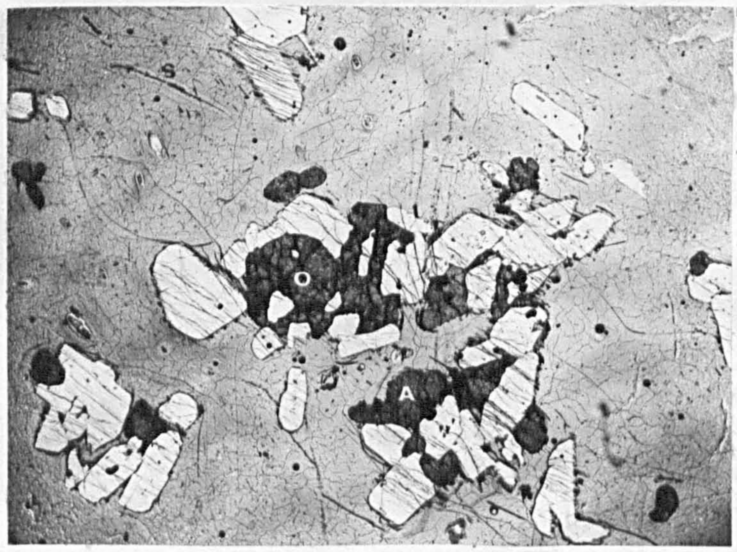
The Marginal Facies (Fig. 64). The sheet margins are of lustrous blue pitchstone which is seen in thin section as a pale brown glass bearing scattered single or clustered crystallites up to 0.1 mm. in length; some flow banding may develop and is seen as narrow bands rich in crystallites which curve round the phenocrysts. Some perlitic cracks are present, and also a few lenticular cavities up to 0.3 mm. across which are lined with minute silica fibres perpendicular to the cavity walls; the centres of these cavities are filled with minute spherulites which may be alkali-feldspar cristobalite intergrowths. The glass has $n = 1.482$ ($\pm$ 0.002) which indicates that it has a silica content of about 76 per cent (Huber and Rinehart 1966) and a high water content (Walker 1966). A few small swallow-tailed feldspar laths up to 0.2 mm. in length were found in the groundmass. These are taken to be rapidly crystallized laths of more sodic feldspar.

The mode of this rock is:

Phenocrysts:	Plagioclase	9.1
	Clinopyroxene	1.6
	Olivine	0.2
	Ore	0.4
Glass		88.7

The plagioclase phenocrysts are twinned on albite and Carlsbad laws, and show strong zoning which is largely normal and continuous but may be interrupted by thin shadowy reversed zones. The majority of the crystals are zoned from cores of high-temperature andesine (An_{36-31}) to margins of oligoclase (An_{16}), and this indicates strong fractionation of the acid liquid. The core compositions of the feldspar phenocrysts range from An_{36} to An_{20}, but this range may be only an apparent one, due to some of the crystal sections examined being sections through the broad outer zone of more sodic material. The crystals show euhedral sections ranging from lath-shapes up to 2.5 x 0.5 mm. in size to stumpier, almost equidimensional sections which may show rhombic shape (see Fig. 64).

Fig. 64



The pitchstone margin of the 50° acid sheet south of Raudkollur, showing the considerable variation in shape of the feldspar sections. A large iron-rich olivine crystal (O) is seen to enclose small andesine and ore crystals in the centre of the field, and numerous ferroaugite crystals (A) are seen to be interstitial to the other phenocrysts. Some perlitic cracks and silica lenticles (S) can be seen in the glassy matrix, and also some small opaque ore phenocrysts.

Plane-polarized light, x 15 (Specimen Vi 178).

A similar variation in habit has been noted in feldspar phenocrysts from British and Icelandic Tertiary glasses by Carmichael (1960a), who finds that many of the plagioclases in these rocks show slender lath forms and that some of the alkali feldspars show almost equidimensional form. Although no detailed study of the form of plagioclases in the Vididalsfjall acid rocks has been made, it is generally noticeable that the andesines in the approximate range An_{40} to An_{25} tend to show lath-like sections and a less elaborate twinning pattern than the more sodic plagioclases, which often show a stumpy form.

Iron-rich olivine (fayalite, $Fa_{90.5}$) occurs as fresh faintly pleochroic pale yellow subhedral grains up to 1.2 mm. across (see Fig. 64); the larger grains show no noticeable zoning and often enclose or are interstitial to crystals of the more calcic plagioclase (An_{36-31}) and small ore grains to form poikilitic intergrowths. The smaller olivine grains show more regular equant outlines and are enclosed by phenocrysts of pyroxene and the more sodic plagioclase phenocrysts showing that they are of early crystallization.

Fresh faintly pleochroic pale green euhedral prismatic crystals of ferroaugite ($Ca_{39.5}Mg_{21.5}Fe_{39}$: No. 14, Fig. 90) are present; these may be twinned and are typically up to about 0.8 x 0.4 x 0.4 mm. in size and range up to 1.2 mm. in length. Some crystals show skeletal form, with voids parallel to the prism faces. The pyroxene crystals were not found to show any marked zoning, but one grain showed a pinkish augite core making up about 10 per cent of the crystal by volume; this may represent an earlier formed magnesian augite which was largely resorbed and later provided a nucleus for ferroaugite crystallization in a similar manner to that suggested by Carmichael

(1960b, pp. 329-30). No exsolution lamellae were found in any of these pyroxenes.

The pyroxenes are interstitial to the more calcic plagioclases and the olivine, and enclose small euhedral phenocrysts of ore and apatite; similar pyroxenes enclosing ore grains have been described by Carmichael (1963a).

Opaque ore occurs as small grains up to 0.25 mm. in size which may show elongated or equant sections; these may be associated with small euhedral columnar crystals of pinkish sphene up to 0.1 x 0.02 mm. in size. The ore grains are enclosed by all the other phenocryst minerals showing that they were the first phenocrysts to form; these ore grains are similar to the titanomagnetites described from Icelandic glasses by Carmichael (1963a) and are taken to be of similar composition.

Apatite occurs as small euhedral rods up to 0.2 mm. in length, showing a length to breadth ratio which varies from 6 to 20:1; a few euhedral stumpy rods of zircon up to 0.1 mm. in length were also found in the pitchstone, and these were sometimes seen to be enclosed by pyroxene phenocrysts.

The Main Facies. The central part of the sheet contains the same phenocryst types as the marginal facies set in a fine-grained quartzo-feldspathic matrix which is really an extremely fine-grained granophyre formed by numerous small randomly oriented lath-shaped feldspars up to 0.1 mm. in length; these crystals show closely-spaced lamellar twinning and strong zoning and are of similar type to the small swallow-tailed laths seen in the marginal pitchstone. The margins of many of these crystals pass out into extremely fine-fret micrographic intergrowths with quartz and thus the feldspars are felt to be sodic plagioclase zoned continuously to an anorthoclase-type feldspar.

Minute subhedral ore grains also occur in this matrix, together with small rods of apatite, pinkish columnar sphene crystals and pink faintly pleochroic zircons. No clinopyroxene grains were found in this matrix, and there is evidence that the liquid did not crystallize to completion, as honey-coloured patches of devitrified glass are abundant in the rock.

The feldspar phenocrysts show a much broader range in zoning from cores of oligoclase (An_{30}) down to margins of more sodic feldspar (An_9). One crystal was found to have a core of high-temperature oligoclase (An_{23}, $2V_\alpha = 65^\circ$) zoned to a margin with $2V_\alpha = 52^\circ$; the composition of this margin is taken to lie within the anorthoclase range (MacKenzie and Smith 1956; Carmichael 1960<u>a</u>). Some of these anorthoclase rims pass continuously into the micrographic groundmass feldspar which is thus taken to be anorthoclase. No phenocrysts were found to have micrographic overgrowths, although all the crystals examined showed marginal overgrowths of alkali feldspar.

All the ferromagnesian phenocrysts in the rock are hydrothermally altered; the olivines are pseudomorphed by carbonate, ore, and honey-coloured serpentinous material. All the pyroxene phenocrysts examined had a narrow rim of honey-coloured glassy material, and these margins were often seen to be embayed. This is taken to indicate that these crystals were not in equilibrium with the later part of the differentiating liquid and underwent reaction and resorption.

The increased continuous zoning range of the feldspars towards more sodic anorthoclase rims indicates that considerable differentiation of the acid liquid occurred at the level of observation after the formation of the glassy margins of the sheet. This state of affairs is explained by Carmichael (1963b, p. 110), who states: "Crystallization of an Icelandic acid liquid under conditions of fractionation, rather than equilibrium, forces the liquid more rapidly towards the base of the ($CaAl_2Si_2O_8$-$NaAlSi_3O_8$ - $KAlSi_3O_8$ - SiO_2) tetrahedron and thence to the ternary minimum. Such fractionation may be achieved by zoning of the feldspar phenocrysts, so that crystals with cores of plagioclase zoned continuously to anorthoclase would result."

The rock described clearly does not represent a liquid which has reached the ternary minimum, as it does not contain quartz phenocrysts and contains interstitial glass.

(b) The Gálgagil Acid Minor Intrusions

The Dykes and Sheet. These intrusions are formed of rhyolitic rock types, similar to that of the Raudkollur intrusion, and are all somewhat hydrothermally altered, the dykes having fine-grained margins of white rock which may represent an original development of pitchstone at the contacts.

The rock is felsitic and uniformly holocrystalline in texture, and bears euhedral phenocrysts of sodic plagioclase; these crystals form up to about 9 per cent by volume of the rock and show lath-shaped sections up to 2.5 mm. in length and near-equidimensional sections up to about 1.0 mm. in length. These crystals are turbid and are twinned mainly on albite and Carlsbad laws, but are often partly replaced by carbonate and epidote, and appear to be almost unzoned.

Small pseudomorphs after pyroxene are moulded on to the feldspar phenocrysts, and these are aggregates of chlorite, carbonate, epidote and ore which show euhedral octagonal and elongated sections which indicate that the original pyroxene formed prismatic crystals up to 1.0 x 0.4 mm. in size. Some small euhedral titanomagnetite grains showing sections up to about 0.3 mm. in length are seen to be enclosed by the pyroxene and feldspar grains, indicating that they were the first phenocrysts to form, as in the Raudkollur intrusion.

The groundmasses of the dykes and the small sheet ("As" on Map 2) are quartz-alkali feldspar fabrics with patchwork texture and abundant small quartz pseudomorphs after platy tridymite crystals. Small granules of ore are dotted throughout the groundmasses, and small needles of apatite are also present; a few stumpy columnar zircon crystals up to 0.1 mm. in length were found. Numerous small pale green acicular ferromagnesian crystals up to about 0.1 mm. in length with length to breadth ratio of 10:1 were found in the groundmass of the east-northeast trending acid dyke at the western end of the Gâlgagil gorge; these have moderate relief and indistinct oblique extinction, the slow vibration direction making an angle of about 20 degrees with the direction of elongation. These crystals have low birefringence, and may be original groundmass clinopyroxene needles now altered to actinolitic amphibole (Deer, Howie and Zussman 1965, Vol. 2, p. 260). Small pyrite grains are also scattered throughout the groundmass; these show square sections up to about 0.1 mm. across and have a brassy lustre in reflected light.

The Acid Breccias. These bodies are formed of holocrystalline rock of finer grain than the dykes and sheet, and contain small turbid feldspar phenocrysts of exactly similar types to those described in the dykes and sheet. No pyroxene phenocrysts were found in these rocks. A few subhedral and anhedral crystals of quartz up to 1 mm. in length were found in two examples of this rock; these show crudely hexagonal or elongated sections up to 1 mm. in length with embayed outlines taken to be indicative of corrosion. These crystals contain numerous small inclusions and may show shadowy twinning parallel to the prism faces. A few euhedral titanomagnetite phenocrysts up to about 0.5 mm. in width also occur in these rocks.

The groundmass of the breccias is a fine-grained quartzo-feldspathic fabric in which small feldspar laths up to about 0.2 mm. can be seen together with small ragged crystals of alkali feldspar and quartz; this texture may indicate that the rock is a devitrified glassy rock which originally contained small feldspar laths.

Small euhedral needles of pale yellow epidote up to about 0.2 mm. in length with a length to breadth ratio of about 5:1 are scattered throughout the groundmass and are felt to be due to hydrothermal alteration; patches of pyrite grains sometimes showing polygonal sections up to 0.2 mm. in width are also abundant in the groundmass and may have a similar origin. These pyrite grains show brassy lustre in reflected light which distinguishes them from the titanomagnetites, and they may be concentrated in late veins and patches in the groundmass; equant grains of clear quartz and alkali feldspar up to 0.2 mm. in width and small epidote needles of similar length also occur in these patches, which range up to about 1 mm. in greatest length in the rocks examined.

The mode of a sample of this rock from Gálgagil was found to be:

Phenocrysts:	Plagioclase	2.9
	Ferromagnesian silicates	0.3
	Ore	tr
	Quartz	tr
Rock fragments		1.8
Matrix		95.0

3-5: ACID MINOR INTRUSIONS IN THE GROUND SURROUNDING VIDIDALSFJALL

Acid dykes from Sida (Vididalsá), Hjallaland and the Kornsá were examined together with the inclined sheet outcropping near the mouth of the Kornsá. These intrusions fall into two main types, the dykes examined being glassy, sometimes hyalopilitic types and the sheet being a holocrystalline type; all these intrusions are altered and no exact determinations of minerals were made in these rocks.

A third type of intrusive acid rock is seen in the Breidabóls-stadur intrusion, and this has glassy and spherulitic modifications.

1. Dykes and Sheets

(a) Glassy Types

The Sida intrusion illustrates the main characteristics of this group and is made of rock which bears plagioclase phenocrysts showing euhedral lath sections up to 1.5 mm. in length which are usually partly or wholly replaced by carbonate. These feldspars show some zoning and are twinned on albite and Carlsbad laws.

Crystals of almost colourless clinopyroxene occur in this rock as euhedral elongated sections up to 1.5 x 0.3 mm. in size and as equidimensional sections up to 0.3 mm. in width, which indicates that the crystals are prisms elongated parallel to the c-axis. Some of these crystals showed faint extremely thin exsolution lamellae parallel to the (001) plane which may indicate exsolution of pigeonite from calcic clinopyroxene (Brown, 1957; Bown and Gay 1960). Many of the crystals show varying stages of alteration to pale green clinoamphibole which may in turn be altered to green chlorite, and other crystals are completely pseudomorphed by chlorite fibres. Some crystals show twinning parallel to (100) and have skeletal form with voids parallel to the prism faces; these voids may be filled with glassy groundmass material. Some of the crystals enclose small early-formed ore grains and may be moulded on to the plagioclase phenocrysts.

Some subhedral pseudomorphs of greenish serpentinic material after olivine were found in this rock, and some of these show well-developed (021) faces and the characteristic irregular cleavage cracks of olivine.

Titanomagnetite forms phenocrysts up to 0.5 mm. in length which may be enclosed by the pyroxene and feldspar phenocrysts, and which show some overgrowth which may be moulded on to the feldspars.

All the phenocryst minerals commonly occur as single crystals in this rock.

The groundmass of the rock is an extremely fine-grained pale brown fabric of minute interlocking quartz and alkali feldspar grains which is taken to represent a devitrified glassy matrix. Small laths of feldspar up to 0.15 mm. in length are abundant in this matrix and form parallel flow trains which curve round the phenocrysts; small ore granules are dotted throughout the matrix, and some small euhedral rods of zircon and apatite were seen.

The Sida rock is interesting in that it includes occasional patches of coarse-grained basic rock up to about 1 cm. in width and similar in texture to the Hólar-Skessusaeti eucrite; these patches are loose crystal clusters of pale pink-brown augite grains up to 4 mm. in length which enclose or are moulded on euhedral plagioclase laths up to about 2 mm. in length. Some small euhedral olivine grains up to 1.0 mm. in length are also present in these clusters; these are pseudomorphed by pale green serpentinous material and may be enclosed by the plagioclase crystals which are often largely replaced by carbonate. Ore is almost absent from the eucrite clusters examined, but one small crystal 0.3 mm. in length was found to enclose a small hexagonal apatite section. The gaps in the clusters are infilled by the matrix material of the dyke; some resorption of pyroxene appears to have taken place, as the augite shows small sigmoidal cavities filled by dyke matrix, but no reaction rims were found.

These basic inclusions are similar to those seen in the early basic cone-sheets and are taken to have been entrained by the acid material before the eucrite liquid had started to precipitate ore in quantity.

To digress, it is of interest to note that these Sida eucrite inclusions occur at a distance of 10 km. west-southwest of the eastern margin of the Hólar eucrite intrusion and 4 km. south of the Borgarvirki intrusion; this is taken to indicate that a large eucritic body may lie at depth beneath the area enclosed by these eucrite occurrences.

The Hjallaland and Kornsá acid dyke rocks are similar in texture and mineralogy to the Sida dyke; the groundmass of the Hjallaland dyke bears smaller feldspar laths than the Sida rock and all the phenocrysts are totally pseudomorphed. The olivine pseudomorphs in this rock show much sharper outlines and apices in section than do those in the Sida rock, and the Hjallaland rock contains scattered small rounded basalt inclusions. No phenocrysts of pyroxene or olivine were found in the Kornsá dyke rock and small pale-coloured acicular clinopyroxene crystals were found in addition to the feldspars in the matrix of this rock. The plagioclases in this rock show strong zoning and the rock bears abundant spherulites up to 1 mm. in diameter. Numerous lenticular cavities up to 1.5 mm. in length were seen in this rock; these are often lined with chalcedony fibres perpendicular to their walls, with central infillings of equant quartz grains or pale brown coloured glass. A few of these cavities were found to contain minute clusters of radially disposed bright green needles, which show similar optical properties to those of celadonite.

(b) Holocrystalline Types

The Kornsá sheet is the only example of this type examined in this section and is really a fine-grained feldsparphyric granophyre which is very poor in ferromagnesian minerals. Only two small chloritic pseudomorphs after pyroxene were found in the section examined, and a few small pseudomorphs after olivine were also found.

The mode of the rock was found to be:

Phenocrysts:	Plagioclase	17.5
	Ferromagnesian silicates	0.9
	Ore	tr
	Quartz	1.5
Matrix		80.1

The plagioclase phenocrysts are seen mostly as lath-shaped sections up to 4 x 1 mm. in size. These crystals are turbid and rather altered, but can be seen to be twinned on albite and Carlsbad laws. Some ore grains of early formation were found in this rock; these are up to 0.4 mm. in length and show a deep red colour at their edges.

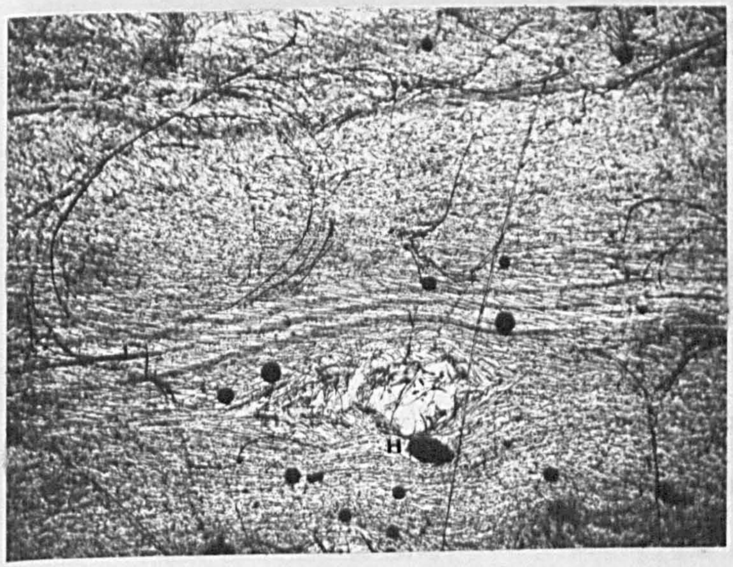
Clear quartz phenocrysts were found to form 1.5 per cent by volume of this rock; these show subhedral equant square or hexagonal sections up to 0.7 mm. in diameter and often have skeletal form and embayed margins (see Fig. 65a). The skeletal form of these quartz phenocrysts may grade into a graphic intergrowth with alkali feldspar, which is taken to indicate that they are of late crystallization. The quartz phenocrysts are invariably surrounded by an overgrowth zone of extremely fine-grained lacy micropegmatite which can be seen to enclose some small feldspar laths. Quartz phenocrysts, although not commonly found in Icelandic acid rocks, have been reported from eastern Iceland (Carmichael 1963b, p. 100; Gibson et al. 1966, pp. 34 and 45) and from the Setberg area, Snaefellsnes (Sigurdsson 1966a, p. 76);

Fig. 65a

The Kornsá acid sheet, showing a bipyramidal quartz phenocryst with c-axis running from the left upper to the right lower corner of the field. The crystal shows skeletal form, and is surrounded by a narrow mantle of very fine-grained quartz-feldspar intergrowth.

Cross-polarized light, x 50 (Specimen K 1).

Fig. 65b



Pitchstone from the margin of the Breidabólsstadur intrusion. An andesine phenocryst with irregular corroded margins can be seen near the lower edge of the field, and below this is a small euhedral amphibole phenocryst (H). The enclosing glass is cut by perlitic cracks and is rich in crystallites aligned in parallel flow trains which curve round the phenocrysts.

Plane-polarized light, x 15 (Specimen Va 35).

the grains described from a holocrystalline acid cone sheet in the Setberg area are rounded, which contrasts strikingly with the angular habit seen in the Kornsá examples. The embayed margins of these Kornsá quartz phenocrysts may be partly due to magmatic corrosion, as advocated by Deer, Howie and Zussman (1965, Vol. 4, p. 212). The presence of quartz phenocrysts indicates that crystallization of the acid liquid took place very near to the ternary minimum of the system: $CaAl_2Si_2O_8 - NaAlSi_3O_8 - KAlSi_3O_8 - SiO_2$ (Carmichael, 1963b).

The matrix of the rock is formed of small lathelike feldspar grains up to about 0.1 mm. in length which show lamellar twinning and may be surrounded by extremely fine-grained micrographic areas. Small equant quartz grains also occur in this matrix, together with small rods of apatite and occasional stumpy columnar zircon crystals up to 0.2 mm. in length. Small crystals of sphene are also scattered throughout the rock, and these are often seen to be associated with the ore grains; this is taken to indicate that sphene was of early crystallization in this rock.

2. The Breidabólsstadur Intrusion

(a) The Marginal Facies

The lustrous black or dark green pitchstone at the margins of this intrusion is a porphyritic rock containing fresh phenocrysts of plagioclase, clinopyroxene, orthopyroxene and amphibole and ore. The mode of this pitchstone is:

Phenocrysts:	Plagioclase	3.0
	Clinopyroxene	0.2
	Orthopyroxene	0.2
	Amphibole	0.1
	Ore	0.1
Glass		96.4

The plagioclase phenocrysts have cores of high-temperature andesine (An_{41-40}) zoned continuously to rims of oligoclase (An_{21}) and occur as clear euhedral crystals up to 0.7 x 1.5 mm. in size; some of these crystals have skeletal form and some may show slightly irregular outlines suggestive of corrosion. These crystals are twinned on albite, Albite-Carlsbad and Carlsbad laws.

The clinopyroxene in the rock is a very pale green ferroaugite ($Ca_{38}Mg_{24}Fe_{38}$: No. 13, Fig. 90) which forms small subhedral prisms up to about 0.5 x 0.3 mm. in size which may be twinned parallel to (100) and which show no noticeable exsolution textures; some slight rounding was seen at the margins of these crystals but no dissolution which might indicate disequilibrium was found. These ferroaugites often enclose small ore phenocrysts and are themselves partly enclosed by the andesine phenocrysts.

The orthopyroxene phenocrysts are small stumpy euhedral prisms up to about 0.3 x 0.1 mm. in size showing good (110) cleavages and distinctive pleochroism from very pale pink to pale grey. The composition of these crystals was found to be about Fs_{35}(p.517) and their margins revealed no trace of corrosion which might suggest disequilibrium; the hypersthene phenocrysts were sometimes seen to enclose small ore phenocrysts and to be enclosed by andesine phenocrysts in the same fashion as the ferroaugites and were found to be more abundant than these pyroxenes. Hypersthene phenocrysts of similarly magnesian composition have been found in other acid glasses from eastern Iceland and the Hebrides by Carmichael (1963a) and the Breidabólsstadur types will be discussed with reference to these examples in the section on mineralogy.

A few small prismatic phenocrysts of pleochroic coffee-brown clinoamphibole up to 0.5 x 0.2 mm. in size were found in the pitchstone and these show euhedral hexagonal sections perpendicular to the c-axis with occasional twinning parallel to (100). These crystals were not seen to be enclosed by other minerals but may be of early precipitation; Carmichael (1967b) found that amphibole phenocrysts from fresh acid glasses had higher iron ratios than their associated pyroxene phenocrysts and suggested that this was due to the earlier precipitation of amphibole relative to pyroxene.

A few small ore phenocrysts were found in the pitchstone, and these are probably of platy form as they show both elongated and equant sections up to 0.3 mm. in length; these crystals were found to be enclosed by both pyroxene types, and are thus taken to be the first precipitates from the acid liquid.

The matrix of the pitchstone is an almost colourless isotropic glass with n = 1.496 (± 0.002) which indicates an approximate SiO_2 content of 71 per cent (Huber and Rinehart 1966). This glass is densely charged with small colourless rod-like and margarite crystallites (Harker 1962, Fig. 50), and these bodies are arranged in parallel flow trains which curve round the phenocrysts in the rock.

The highly silicic nature of the glass contrasts markedly with the rather intermediate character of the phenocryst minerals, the plagioclase and pyroxenes in this rock being of compositions more typical of the Icelandic andesites (Carmichael 1967a) than of rhyolitic rocks. The occurrence of an amphibôle in such a glassy rock is also unusual for Iceland; Walker (1963) has found amphibole phenocrysts in the Kelduskogar rhyolite plug of eastern Iceland and he suggests that in this case the mineral crystallized at about 300-600 m. below the contemporaneous land-surface. It seems possible that the Breidabólsstadur amphibole crystallized at relative depth as the intrusion in which it occurs lies near a vent and is possibly an offshoot of an acid plug (p.282).

(b) The Main Facies

The main facies of the Breidabólsstadur intrusion shows essentially the same texture and mineralogy as the marginal pitchstone, and the only differences found were in the state of alteration of the ferromagnesian phenocrysts and the texture of the groundmass.

The andesine and ore phenocrysts in the main facies rock are identical to those in the marginal glassy rock, but the amphibole, orthopyroxene and clinopyroxene phenocrysts appear to have undergone some hydrothermal alteration and are pseudomorphed by carbonate and fibrous green-brown material.

The fine-grained groundmass of the rock contains numerous flow trains of crystallites like those seen in the marginal pitchstone; small "pin-cushion" clusters formed of densely concentrated crystallites are scattered throughout this material.

The groundmass itself consists of a compact mass of very small contiguous spherulites; these spherulites range up to about 0.5 mm. in diameter and although their individual fibres are too small to resolve, it seems likely that these are of quartzo-feldspathic material. The groundmass material has a cloth-like appearance when viewed with crossed polars, due to the numerous minute polarization crosses of the spherulites, and is identical in appearance to an example figured by Kerr (1959, Fig. 16-43d).

3-6: THE MELRAKKADALUR-URDARFELL GRANOPHYRE INTRUSION

The granophyre of this intrusion shows limited variation in texture and all the types found were feldsparphyric. Some differences in texture were found between the rock in the margins and the main part of the intrusion.

(a) The Marginal Facies

The finest-grained marginal rock was found at the western edge of the Dalså outcrop and is very useful in determining the order of crystallization of the various minerals found within the intrusion. This rock is strikingly spherulitic when seen in thin section, and spherulites up to 1 mm. in diameter make up about 41 per cent by volume of the rock.

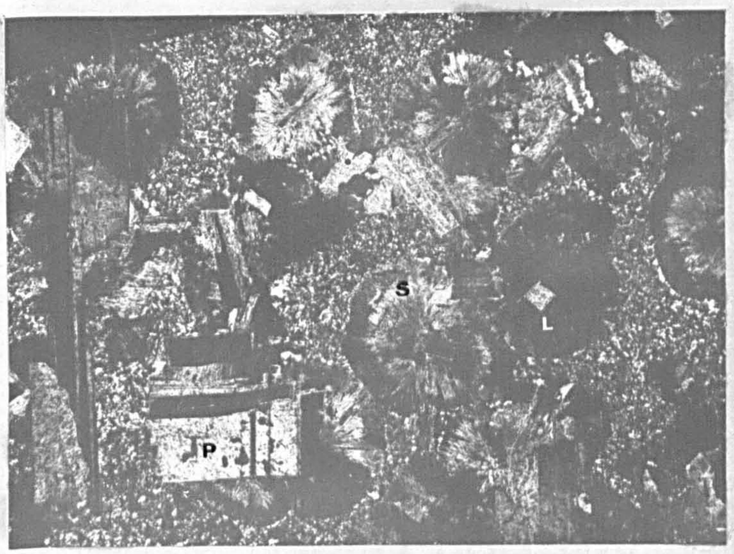
Phenocrysts of plagioclase feldspar and a few yellow-green chloritic pseudomorphs after pyroxene were found in the rock together with some opaque ore grains; the mode of a sample of spherulitic granophyre was found to be:

Phenocrysts:	Plagioclase	17.2
	Ferromagnesian silicates	1.4
	Ore	0.2
	Quartz	0.1
Spherulites		41.4
Accessory minerals (Sphene, zircon, apatite)		tr.
Quartz-Alkali feldspar matrix		39.7

Two main types of plagioclase phenocryst were found in this rock. The first type consists of long euhedral lath and near-equidimensional sections showing respective sizes up to 4 mm. and 1 mm.; these crystals are twinned mainly on albite and Carlsbad laws and show clear cores of andesine or calcic oligoclase (An_{30} to An_{27}). These crystals show continuous normal zoning and invariably have cloudy rims (see Fig. 66a) which were seen to show sharp edges against the spherulitic silica-alkali feldspar growths which partly enclose them. None of these feldspar phenocrysts were seen to be wholly enclosed by spherulitic growths. Occasional pseudomorphs after pyroxene were found to be partly moulded on to these phenocrysts and this is taken to indicate that these two minerals crystallized at an early stage in the cooling history of the rock to form glomeroporphyritic clusters similar to those seen in the fine-grained minor acid intrusions elsewhere in the area. The plagioclase phenocrysts of the second type are much smaller in size than those of the first type and typically form small euhedral crystals of near-equidimensional section up to 0.5 mm. in size. In addition, these crystals are clouded throughout and are twinned on a more elaborate pattern than the larger phenocrysts. The cores of these small feldspars are of sodic oligoclase and show some continuous zoning which passes at the margins into the alkali feldspar component of the spherulitic growths; these growths completely enclose the small feldspar crystals. None of these crystals were found to be associated with pyroxene pseudomorphs, and their composition is taken to indicate that they are the latest-formed feldspar phenocrysts in this granophyre.

These two feldspar phenocryst types found in the MU granophyre show very similar composition and twinning patterns to the two types of feldspar phenocrysts found in the granophyres of the Slaufrudal stock in eastern Iceland by Beswick (1965). In these Slaufrudal

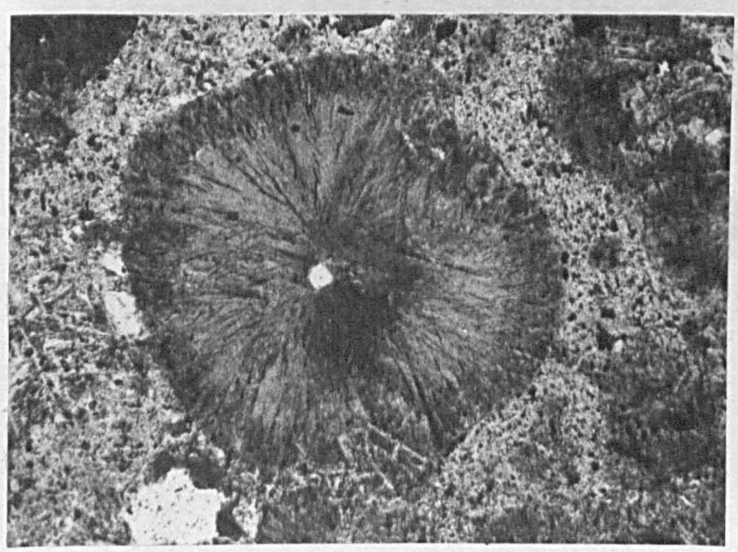
Fig. 66a



Fine-grained spherulitic marginal granophyre from the Dalsá outcrop. Large phenocrysts of andesine-oligoclase plagioclase (P) with clear cores are partly surrounded by spherulitic growths (S). Smaller more sodic feldspar phenocrysts (L) are completely surrounded by spherulitic growths and are cloudy throughout. The fine-grained felsitic groundmass evidences the rapid solidification of this rock.

Cross-polarized light, x 15 (Specimen A9).

Fig. 66b



The fine-grained marginal facies of the MU granophyre in the Dalsá outcrop, showing a small bipyramidal quartz crystal at the centre of a spherulite; the crystal is sectioned parallel to the c-axis (which lies nearly parallel to the page margin) and shows vestigial prism-faces. Small dark needles of ferromagnesian mineral lie within the spherulite, and a patch of interstitial quartz (white) lies at the lower left border of the field. Same section as Fig. 66a.

Plane-polarized light, x 50 (Specimen A 9).

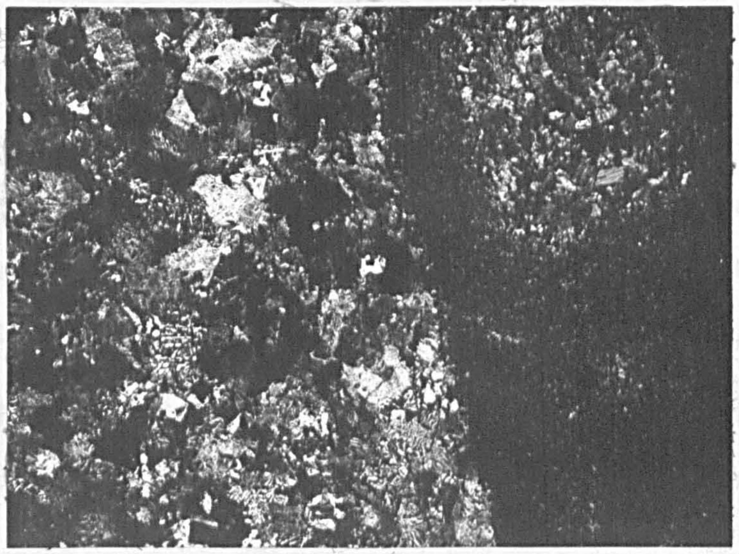


Fig. 67. Contact of granophyre with basalt on northern Urdarfell at the 380 m level. Graphic intergrowths of quartz and alkali feldspar are abundant in the acid rock, which shows no appreciable decrease in grain size towards the contact. A vesicle in the basalt can be seen to be occupied by small blade-like crystals of biotite and pale green clinoamphibole (see p. 286).

Cross-polarized light, x15 . (Specimen Vi 221).

granophyres, strongly-zoned andesine-oligoclase plagioclase is seen to occur as clear crystals of elongated habit in which twinning is sometimes absent or only weakly developed. Pericline twinning is rare in these crystals and they are often seen to be fractured. The second type of Slaufrudal feldspar phenocryst is on albite, Carlsbad and pericline laws; these crystals have compositions in the oligoclase-albite-anorthoclase range (Beswick, op. cit.).

Beswick (op. cit.) has described the textures of the Slaufrudal acid rocks in detail on the basis of examination of a large differentiated acid stock. The MU intrusion is not so well or so extensively exposed as the Slaufrudal stock, so that a complete classification of its different rock types is not possible; Beswick's petrographic classification of the Slaufrudal acid intrusives has therefore been used to maintain consistency in the description of similar rock types from the same igneous province.

The marginal facies of the MU granophyre contains small opaque ore phenocrysts which show subhedral equant sections up to about 0.5 mm. in width; these grains were sometimes seen to enclose small euhedral rhombic sections of pale pink sphene up to about 0.2 mm. in width. These ore phenocrysts are taken to be the first-formed phenocrysts as they are enclosed by both andesine and pyroxene phenocrysts.

Small clear quartz phenocrysts were also found in this marginal facies; these often show euhedral square sections which are usually up to 0.5 mm. in width and are often surrounded by spherulitic intergrowths of the same type as those seen to enclose the feldspar phenocrysts (see Fig. 66h). The quartz phenocrysts in the marginal granophyre on southwestern Urdarfell tend to show more ragged form which may indicate that these grains have undergone corrosion; many of these grains are not surrounded by spherulites.

Bright green chloritic pseudomorphs after pyroxene are seen in the marginal granophyre, and these show elongated sections and euhedral octagonal sections up to 3 mm. and 0.5 mm. in length. These grains occur in the glomeroporphyritic clusters where they are moulded on to the andesine-oligoclase grains and enclose small ore phenocrysts which have sub-hedral square sections up to 0.5 mm. in width.

The groundmass of the marginal granophyre is a fine-grained felsitic fabric of interlocking quartz and alkali feldspar grains which shows some variation in grain size in different parts of the outcrop; the marginal rock on northern Urdarfell shows almost no development of a felsitic groundmass (see Fig. 67). This variation in grain-size of the margins does not appear to occur systematically. The coarser-grained margins may however represent contacts of granophyre against country rock blocks which sank into the more completely crystallized inner parts of the hot granophyre; alternatively, these coarser-grained margins may represent parts of the intrusion which were intruded into warm country rock.

Small grains of sphene and zircon are scattered throughout the groundmass and small pale green needles of clinopyroxene up to 0.2 mm. in length were found in some samples of the margin. Small green needles of this type were found in the spherulites in the Dalsá rock where they show indistinct extinction and may be pseudomorphed by pale green chloritic material; these are felt to be altered clinopyroxene needles. A few euhedral prismatic crystals of brown allanite up to about 0.1 mm. in length were found in the spherulites of the Dalsá rock, and the outer parts of these spherulites appear to be made of small platy paramorphs of quartz after tridymite which show elongated sections.

The thin veins which pass from the MU granophyre intrusion to cut the felsite in the Dalsá (p. 195) are of granophyre similar to that seen at the northern contact of the main intrusion on Urdarfell (see Fig. 67) and contain small phenocrysts of plagioclase, bipyramidal quartz and pseudomorphs after ferromagnesian silicates.

The general spherulitic texture of this marginal facies of the MU granophyre is similar to that of the granophyre sill of southern Raasay in the Hebridean Tertiary area (Davidson, 1935, p. 389), and this Raasay rock also bears quartz phenocrysts. Beswick (1965) has described spherulitic granophyres from the Slaufrudal stock.

(b) The Main Facies

The marginal facies of the MU granophyre grades into the coarser-grained main facies of the intrusion by increase in the volume and number of the individual graphic intergrowth mantles to the feldspars, which proceeds pari passu with the disappearance of the felsitic groundmass seen in the marginal facies. These features are clearly seen in the modes of the two rocks (see p.365); the mode of the main facies granophyre in the Dalsá was found to be:

Phenocrysts:	Plagioclase	20.9
	Ferromagnesian silicates	0.2
	Ore	0.7
	Quartz	0.3
Graphic material		66.6
Accessory minerals, etc. (sphene, zircon, apatite, epidote, allanite and carbonate)		3.7
Interstitial non-graphic material:	Alkali feldspar	5.7
	Quartz	1.9

The two types of feldspar phenocrysts seen in the marginal facies are still distinguishable, although the more basic elongated types often show a greater degree of clouding, and may be partly or totally pseudomorphed by carbonate, epidote and alkali feldspar; a similar alteration has been noted in the more basic feldspar phenocrysts of the Slaufrudal granophyres by Beswick (1965). Spherulites are also apparently absent from the main facies of the granophyre and this may be a result of the slower rate of cooling of the inner part of the intrusion; Beswick (op. cit.) suggests that the spherulite content of the Slaufrudal granophyres may be a function of the degree of chilling. No spherulites were found in the MU granophyre at distances greater than about 4 m. from the contacts.

Ferromagnesian phenocrysts are extremely rare in the main facies of the granophyre and those found were bright green-yellow pseudomorphs of exactly similar type and size to those seen in the marginal facies, occurring as elongated grains moulded on to plagioclase phenocrysts in clusters. A few small ore phenocrysts were also found in the main facies granophyre, and a few small bipyramidal quartz phenocrysts identical to those in the marginal facies were seen to be enclosed by fine-fret graphic intergrowths.

The graphic quartz-alkali feldspar intergrowths in this rock show some variation in texture, and there is apparently continuous variation in fret size from types bearing extremely fine-grained quartz fibres to types in which the quartz fibres (or tubules) set in the alkali feldspar may be up to 0.2 mm. in cross-sectional width. These tubules are positioned with their long axes perpendicular to the faces of feldspar phenocrysts and appear in section as lacy fretworks of elongated quartz grains which increase in width away from the enclosed feldspar crystal; these intergrowths form broad rims up to about 0.5 mm. in breadth to the feldspar and occasional small quartz phenocrysts. The alkali feldspar in these intergrowths is cloudy in appearance, and this may be due to unmixing of a feldspar originally of anorthoclase type , by analogy with the similar textures seen in the alkali feldspars of the Slaufrudal stock granophyres, which have been shown to be anorthoclase cryptoperthites (Beswick 1965).

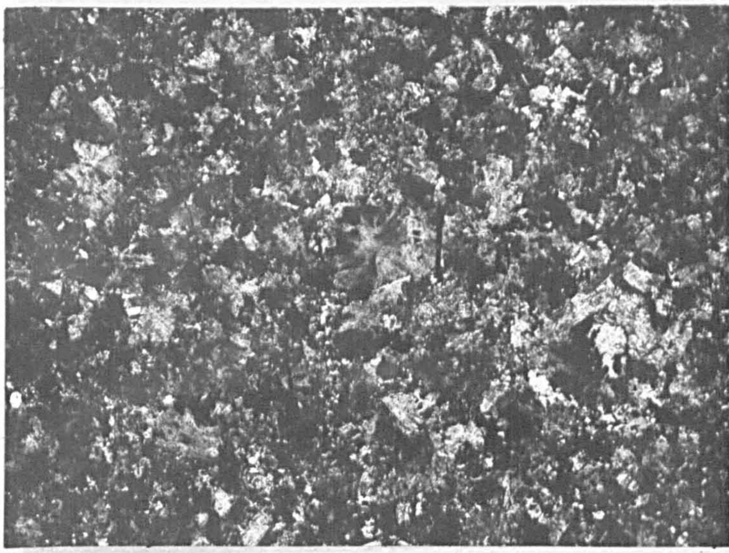
The finest-grained of the fine-fret intergrowths are almost spherulitic in appearance, and may represent the earliest-formed intergrowth rims to feldspar phenocrysts, by analogy with those seen in the marginal facies of the granophyre (see Fig. 68a).

No felsitic ground mass was seen in the main facies granophyres, and the spaces between the feldspar-intergrowth units are occupied by grains of clear quartz and turbid alkali feldspar. Some small euhedral crystals of sphene, zircon and apatite were seen in these interstices, together with rare prisms of brown allanite.

Miarolitic cavities up to about 5 mm. in length are abundant in the main facies granophyre; these voids account for up to about 8 per cent of the total volume of the rock, and provide a further textural feature which serves to distinguish the main facies from the quickly-cooled marginal facies. These cavities are lined with small euhedral needles of pale yellow epidote up to about 0.15 mm. in length and euhedral clear quartz prisms up to about 5 mm. in length, the latter often showing well-developed terminal faces. Occasional small euhedral clear alkali feldspar crystals with tabular sections were sometimes seen to be enclosed by these quartz crystals, and these show elaborate twinning patterns. The centres of some cavities were seen to be infilled by clear carbonate grains.

No crystals of biotite, fluorite or tridymite were found in the main facies granophyre.

Fig. 68a



Fine-grained granophyre from 1.5 m. below the upper contact of the intrusion at the 450 m. level on northern Urdarfell, showing the scarcity of spherulites away from the contact. A small spherulite lies in the centre of the field and the matrix of the rock is of noticeably coarser grain than than in Fig. 66a.

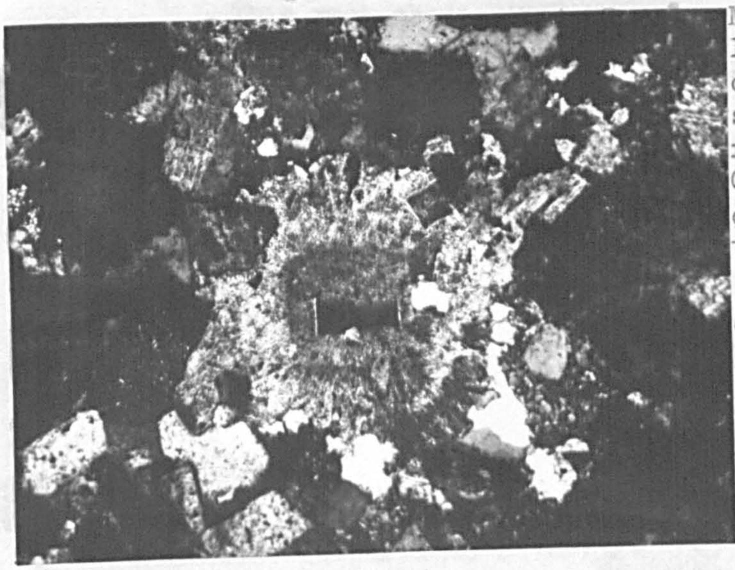
Cross-polarised light, x 15 (Specimen Vi 189).

Fig. 68b

Medium-grained granophyre from 3.5 m. below the upper contact at 300 m. on western Urdarfell, showing fine- and medium-coarse-fret graphic intergrowths which often surround small cloudy feldspar phenocrysts.

Cross-polarized light, x 15 (Specimen Vi 125).

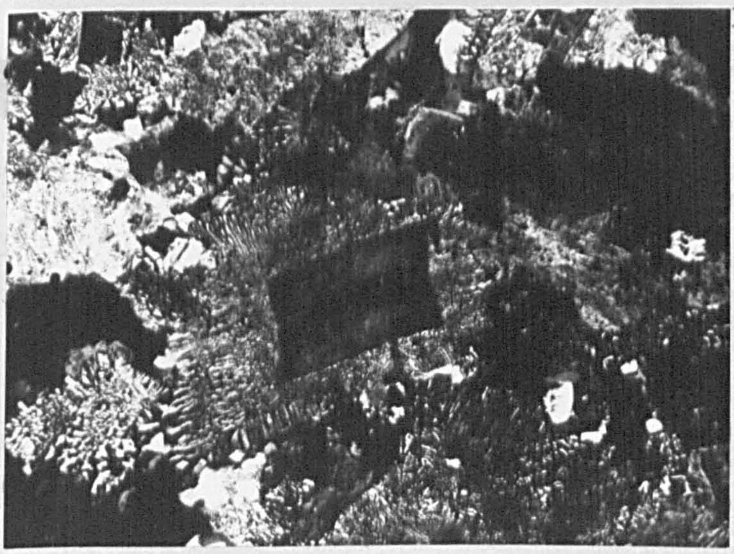
Fig. 69a



Main facies granophyre from the Dalsá outcrop, showing the development of fine-fret, almost spherulitic graphic intergrowth rims round feldspar phenocrysts. Grains of later-precipitated quartz (white) can be seen in the interstices of the rock.

Cross-polarized light, x 45 (Specimen Vi 38).

Fig. 69b



Main facies granophyre from the Dalsá outcrop, showing the development of medium-coarse-fret graphic intergrowth rims about feldspar phenocrysts. The outward coarsening of the frets can be seen at the lower left border of the intergrowth in the centre of the field.

Cross-polarized light, x 45 (Specimen Vi 38).

(c) Pyroxene Granophyre

This rock shows similar textures to the main facies granophyre of which it forms a part, but, like the marginal facies granophyre of the Dalsá outcrop, is richer than the main facies granophyre in ferromagnesian phenocrysts as can be seen from its mode, and bears glomeroporphyritic clusters of sodic clinopyroxene, ore, clear plagioclase and pseudomorphs after olivine. The mode of the rock was found to be:

Phenocrysts:	Plagioclase	15.2
	Sodiclinopyroxene	0.7
	Olivine	1.7
	Ore	0.3
Matrix:	Sodic amphibole	1.3
	Accessories (sphene, zircon, apatite and allanite)	0.1
	Quartz and alkali feldspar	80.7

The clinopyroxene in these rocks occurs as prismatic crystals elongated parallel to the c-axis which show elongated sections up to 1.5 mm. in length and euhedral octahedral sections up to 0.5 mm. in width. The centres of these grains are generally of a pale green colour which intensifies to a darker bright green colour at the margins of the crystals; these crystals are of aegirine-augite which was found to contain about 40-50 per cent of the aegirine molecule. Similar occurrences of green sodic pyroxene have been found in eastern Iceland in the granophyres of Slaufrudal (Beswick 1965), the Austurhorn intrusion (Blake 1966), and the Ketillaugarfjall intrusion of the Hornafjördur area (Annels 1967).

The pyroxene phenocrysts in the Urdarfell rocks are moulded on to the andesine-oligoclase phenocrysts and were seen to enclose small subhedral ore grains of early crystallization, together with small euhedral crystals of apatite and sphene.

Some honey-coloured pseudomorphs after olivine were also found in the phenocryst clusters; these are approximately equant in section, and were often found to show euhedral form with well-developed (021) faces. These olivine crystals were sometimes found to enclose the small ore and sphene phenocrysts and to be partly enclosed by the plagioclase and pyroxene phenocrysts, indicating that they are of relatively early crystallization. By analogy with the olivine phenocrysts seen in the minor acid intrusions of Vididalsfjall (see p.348) and those described from the granophyres of the Austurhorn intrusion (Blake 1966), these olivines are taken to have been of originally highly fayalitic composition.

The matrix of these pyroxene granophyres is similar in mineralogy to that described for the main facies granophyre, but appears to be of more equigranular texture, consisting of approximately equant grains of alkali feldspar and quartz with occasional interstitial patches of medium-fret graphic intergrowth. Rocks of similar texture, to be described later, are found in the southern Urdarfell fault gully, and these are similar to types described as "granitic" from the Slaufrudal stock by Beswick (1965).

The granitic groundmass of the Urdarfell rock was found to contain a very dark blue-green pleochroic amphibole in small ragged grains up to 1.5 mm. in length which have optical properties similar to those of arfvedsonite; these amphibole grains sometimes show euhedral rhombic cross-sections with intersecting (110) cleavages and they appear to be of late crystallization, as they are often seen to be interstitial to the quartz and feldspar grains of the groundmass. A few of the dark blue-green grains were seen to poikilitically enclose small clear euhedral tablets of late-stage alkali feldspar similar to that seen in the miarolitic cavities; in addition, the amphiboles were sometimes seen to enclose small crystals of apatite, and one grain was found to be moulded on to a late-stage quartz crystal which was moulded in turn on to a feldspar-pyroxene-olivine phenocryst cluster.

Few occurrences of sodic amphiboles are known in Iceland, but examples have been found in the Ketillaugarfjall granophyre ring-dyke by Annels (1967); these examples are arfvedsonite types which are intimately associated with aegirine-augite and may vein crystals of this mineral (Annels, op. cit.). No such relations with aegirine-augite were found in the Urdarfell rock.

Sodic amphiboles have been found in a number of acid rocks from the Hebridean Tertiary Igneous Province, notably in the Meall Dearg, Druim an Eidhne and Marsco granophyres of Skye (Harker 1904, p. 158), the Maol na Gainmich Epigranite of Skye (Wager et al. 1965, p. 279), the granophyre of southern Raasay (Davidson 1935, p. 390) and the Ailsa Craig microgranite (Teall 1891); the amphibole in these rocks is a riebeckite type.

3-7: THE URDARFELL-ACID-INTERMEDIATE HYBRID BODY

1. Diorite

(a) Marginal Facies

This rock is a medium-coarse-grained fabric of euhedral to subhedral crystals of plagioclase, clinopyroxene and ore set in a fine-grained acid matrix.

Plagioclase occurs in this rock as randomly oriented euhedral columnar phenocrysts with clear cores of labradorite to andesine (An_{52} to An_{41}) which are continuously zoned to margins of oligoclase (An_{21}) and may show skeletal form with forked terminations; these plagioclases have intermediate to high temperature optics. The margins of the plagioclases are usually slightly cloudy and are surrounded by a fine-grained felsitic acid groundmass (see Fig. 70). The plagioclase crystals in the rock range up to a size of about 1.7 mm. with a length to breadth ratio of about 3:1, and were found to be twinned mainly on albite and Carlsbad laws, with occasional developments of very narrow pericline twins. A few minute inclusions of ore and ferromagnesian material were found in the cores of some plagioclase phenocrysts.

The continuously zoned outer part of these plagioclase phenocrysts shows a change in anorthite composition from about An_{40} to An_{21} over the outermost 7-15 per cent of the crystal width, indicating that this part of the crystal grew quickly in a liquid undergoing rapid fractionation; these rapidly formed outer zones are easily recognised in thin section, and are found in all the rocks of the hybrid group.

Fig. 70

The medium-grained marginal facies of the diorite on southwestern Urdarfell, showing small columnar labradorite-andesine crystals, some of which have skeletal form, and small pyroxene and ore crystals set in a fine-grained acid matrix. An acicular apatite crystal can be seen near the lower right corner of the field.

Plane-polarized light, x 15 (Specimen Vi 215).

Clinopyroxene occure in the marginal facies of the diorite as small prisms of pale pink-brown calcic augite up to about 1.5 x 0.25 mm. in size which often show twinning parallel to (100) and may have euhedral octagonal cross-sections perpendicular to the c-axis. These crystals are often seen to be partly moulded on to the plagioclase crystals and many show very thin exsolution lamellae parallel to (001) which are possibly of pigeonite (Brown 1957; Bown and Gay 1962) and are similar in appearance to those found in the augites of the Hólar-Skessusaeti intrusion. No zoning was found in these crystals, and no pigeonitic rims were detected by optical methods. Opaque ore occurs in this rock as elongated or polygonal sections up to about 1 mm. in size which often show skeletal form; these grains are believed to have been formed during the later stages of cooling of the rock as they are often seen to be moulded on to grains of plagioclase and pyroxene.

No olivine was found in this marginal facies.

The matrix of the rock is a pale pink-brown alkali feldspar-quartz fabric, of turbid appearance, in which these two minerals are usually intergrown in an extremely fine-grained graphic texture which is only just visible under a high-power objective; this fine-grained material is similar in appearance to that in the Hólar schliere (Fig. 56) and sometimes passes into a medium-fret graphic intergrowth which mantles but is not continuous with the outermost rims of the strongly-zoned plagioclase crystals. No small groundmass plagioclase crystals were found in this matrix.

Apatite is common in the matrix material as thin rods up to 2 mm. in length with a length to breadth ratio of 20-40:1, or as shorter more stumpy columns. A few minute euhedral crystals of sphene and zircon were also found in the matrix; one zircon crystal was found to have a homoaxial overgrowth of colourless material which may be apatite; Larsen and Poldervaart (1957, p. 558) have observed similar apatite overgrowths on zircons in tonalites.

A few small cavities in the rock were found to be lined by small euhedral prisms of clear quartz and centrally infilled by carbonate; these may be miarolitic cavities by analogy with those seen in the MU granophyre.

The general texture of this marginal diorite suggests that it cooled rapidly and it is very similar in appearance to the plagioclase-pyroxene orthocumulate schliere found in the northern margin of the Hólar intrusion (see Fig. 56) except that the plagioclases in the Hólar rock were not found to show the strongly-developed marginal zoning seen in the Urdarfell plagioclases. The plagioclases in the Hólar schliere were found to show high-temperature optics with cores of An_{55} zoned continuously to rims of An_{36}; this zoning range overlaps the more calcic part of the range determined for the Urdarfell feldspars, and as general field relationships indicate that the Hólar schliere and the Urdarfell diorite margin are probably contemporaneous, it is suggested that these two similar rock types may be cogenetic plagioclase cumulates.

Beswick (1965) has described hybrid rocks similar to the Urdarfell marginal diorite from the Slaufrudal stock; the plagioclases in the Slaufrudal rocks are seen solely as phenocrysts which are strongly zoned from cores of andesine to margins of oligoclase. The Slaufrudal rock bears biotite, amphibole and chlorite set in a groundmass of finely microgranitic or felsitic texture which lacks plagioclase laths and commonly contains glomerogranular patches of coarse quartz and alkali feldspar grains (Beswick, op. cit.).

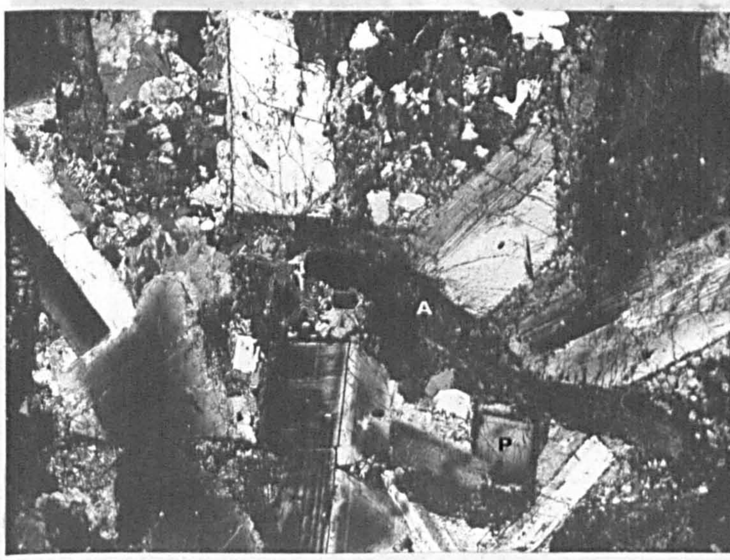
(b) Main Facies

The mineralogy of this rock is similar to that of the marginal facies and the rock forms the bulk of the diorite exposures found on southwestern Urdarfell. The mode of the rock is:

Plagioclase	49.1
Clinopyroxene	16.3
Amphibole and chlorite	1.0
Ore	3.1
Accessory minerals (sphene, zircon and apatite)	1.3
Graphic quartz-alkali-feldspar material	29.2

The plagioclase in this rock forms larger grains than those seen in the marginal facies; these being large euhedral columnar phenocrysts up to about 4 mm. in length which often show square sections up to 2 mm. in width perpendicular to the c-axis, and are twinned on the same laws as the marginal facies plagioclases. These larger plagioclases appear to be slightly less calcic than those seen in the marginal facies, having cores of labradorite-andesine ($An_{52.5}$ to An_{38}) which are zoned to rims of oligoclase (An_{21}); the outer, more sodic zones show the same rapid change in composition over the outermost 10 per cent of

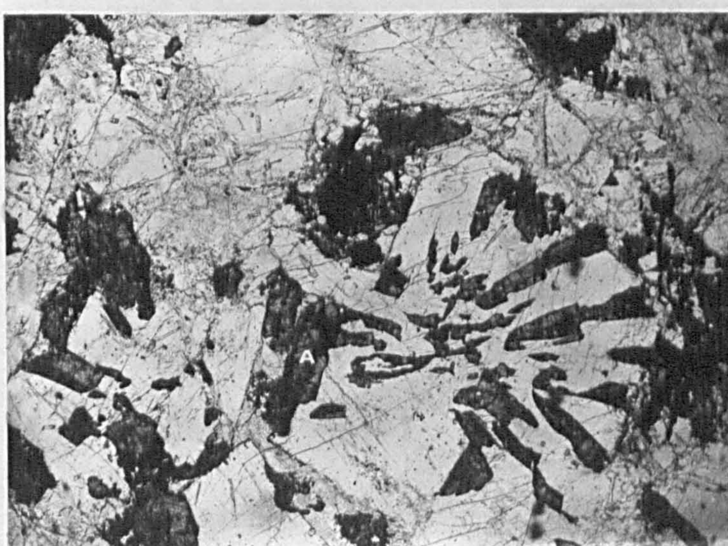
Fig. 71a



Main facies diorite at the 250 m. level on southwestern Urdarfell, showing large phenocrysts of labradorite-andesine plagioclase (P) with strongly zoned rims set in a granitic matrix. A large elongated augite phenocryst (A) in the centre of the field shows a curved form where plagioclase phenocrysts rest against it. A few grains of opaque ore are seen to be associated with the pyroxene.

Cross-polarized light, x 15 (Specimen Vi 398).

Fig. 71b



Main facies diorite from the same specimen as that shown in Fig. 71a, showing a large plagioclase crystal in graphic intergrowth with augite (A).

Plane-polarized light, x 15.

Fig. 72

Main facies diorite from the 220 m. level on southwestern Urdarfell, showing large corroded and strongly zoned andesine phenocrysts (P), lying in a largely granular granitic matrix of quartz (white) and turbid alkali feldspar.

Cross-polarized light, x 15 (Specimen Vi 116).

the crystal width as do those of the marginal facies. These outermost zones pass into turbid sodic rims which are mantled discontinuously by the alkali feldspar of the matrix. These alkali feldspar mantles do not completely surround the plagioclase crystals.

The clinopyroxene in this rock is a pale pink-brown calcic augite ($Ca_{40}Mg_{37}Fe_{23}$: No. 10, Fig. 90) which forms prismatic crystals up to 4 mm. in length and 0.5 mm. in width which appear to be unzoned and are often seen to be twinned parallel to (100). A number of crystals were found to show very thin lamellae of low birefringence developed parallel to (001); these are felt to be of exsolved pigeonite, and are similar in appearance to those seen in the augites of the marginal diorite. Many of the augite grains in this rock were found to show homoaxial rims of a pale brown clinoamphibole which is often altered to chlorite; this development of amphibole rims to pyroxene grains is similar to that described in the dioritic rocks of the Cairnsmore of Carsphairn complex (Deer 1935) and will be discussed later. Other augite grains are clouded by the presence of numerous minute opaque ore particles similar to those seen in the augite phenocrysts of the dolerite margin of the Hólar-Skessusaeti eucrite intrusion (see Fig. 55); the ore particles in the diorite augites were not found to be grouped into concentric zones as are those in the dolerite augites. In other augites within the diorite the pyroxene grains were found to bear small ore blebs arranged in regular graphic textures, and this may indicate that in these instances the pyroxene and ore were of simultaneous crystallization.

The pyroxene crystals show different relationships towards the plagioclase phenocrysts even within the same thin section (see Fig. 71b). A number of euhedral plagioclase phenocrysts were found to bear numerous units of augite showing simultaneous extinction and arranged in graphic intergrowth patterns similar in form to the quartz-alkali feldspar intergrowths of the matrix; these intergrowths may be due to simultaneous crystallization of plagioclase and pyroxene, by analogy with the widely-believed interpretation of the origin of quartz-alkali feldspar intergrowths. In other parts of the same section (see Fig. 71a) the pyroxene may occur as elongated crystals which are seen to be bent across the tips of plagioclase phenocrysts; this is taken to be due to movement of early-formed phenocrysts of the two minerals in the interstitial liquid, but may be due to readjustments within the crystal mesh during cooling and consolidation of the diorite.

No olivine grains were found in this main facies rock.

Elongated ore grains up to 3 mm. in length with skeletal form occur in this rock and often show elongated sections; these show the general properties of ilmenite, and are interstitial to the plagioclase and pyroxene grains. A few grains were found to have small fringes of small biotite blades, and some ore grains were seen to enclose small euhedral grains of apatite and sphene. This textural evidence is taken to indicate that ore was of late crystallization in this rock.

The spaces between the plagioclase, pyroxene and ore crystals are occupied by a largely equigranular granitic matrix of clear quartz and turbid alkali feldspar grains up to about 0.3 mm. in width (see Fig. 72); parts of this matrix show graphic intergrowth of the felsic components and the alkali feldspar grains were not seen to be continuous with the alkali feldspar in the graphic areas adjacent to the plagioclase phenocrysts. Examination of these alkali feldspar areas under a high-power objective indicated that the clouding may be due to the development of minute exsolution lamellae in the feldspar.

The matrix areas were also found to contain ore grains and small elongated pyroxene grains of similar appearance to those seen in the more basic part of the rock; these small elongated ore and pyroxene grains appear to decrease in abundance towards the centre of the light-coloured granitic areas and this confirms the general features observed in hand-specimens of the diorite (see Fig. 32).

Small euhedral crystals of apatite, sphene and zircon were also found within the granitic matrix and the general texture of these medium-coarse glomerogranular patches is similar to that of the coarse-grained H_G acid rock seen in the southern Urdarfell fault gully.

The Urdarfell dioritic rocks show distinct textural features consistent with an origin by crystal accumulation; these are particularly noticeable in those parts of the diorite poor in pale-coloured patches of granitic material and these rocks are texturally very similar to the andesinites of the Upper Border Group of the Skaergaard Intrusion (Wager and Deer 1939; Wager and Brown 1968) which have been shown to have originated by accumulation of andesine plagioclase in an iron-rich liquid belonging to an advanced fractionation stage of the original Skaergaard liquid. These Skaergaard rocks contain iron-rich augite, occasional altered olivine and some quartz and micropegmatite as the intercumulus material; this iron-rich augite contrasts with the more magnesian cumulus pyroxene of the Urdarfell diorite ($Ca_{40}Mg_{37}Fe_{23}$) which has a composition equivalent to that of the calcium-rich pyroxene cumulus phase found in the approximate position of the junction between the Lower and Middle Zones (LZ and MZ) of the Skaergaard Layered Series (Wager and Brown, op. cit.). The average composition of the Urdarfell diorite augites is near that of the cumulus augites in the marginal dolerite of the Hólar-Skessusaeti intrusion, which was determined as $Ca_{40}Mg_{40.5}Fe_{19.5}$; the close correspondence of the cumulus plagioclase and clinopyroxene compositions in the Urdarfell diorite and the marginal dolerite of the Hólar-Skessusaeti intrusion together with the evidence of their almost simultaneous emplacement is thus taken to indicate that these rocks may have originated from liquids of very similar chemical composition which lay close together on the same liquid line of descent. The Urdarfell minerals are slightly richer in soda and iron than those in the Hólar-Skessusaeti rock, and the liquid from which they formed would therefore lie farther down the liquid line of descent than that of the marginal dolerite.

(c) Schlieren in the Diorite

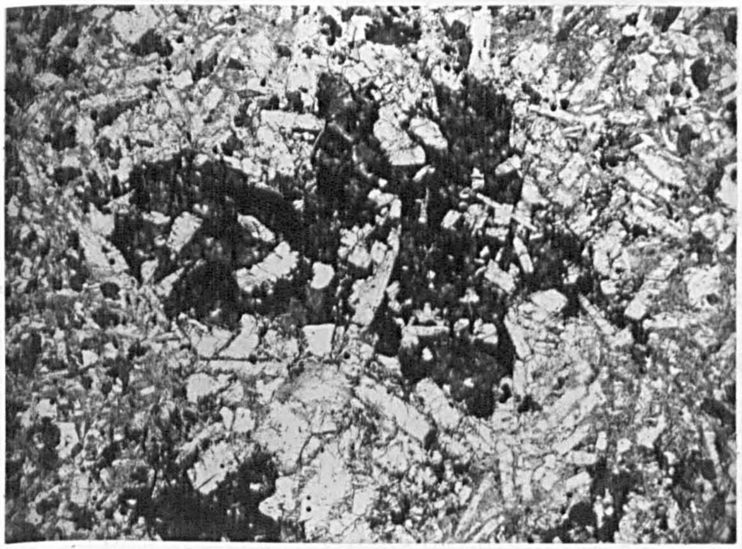
These bodies are composed of a rock very similar in texture and grain size to the marginal facies of the diorite, but the plagioclase phenocrysts which make up the bulk of the fabric were found to have more sodic core compositions than those in the marginal facies, showing a total zoning range from cores of andesine (An_{47}) to oligoclase (An_{21}); these crystals also show apparently continuous rims of cloudy alkali feldspar which are broader than those in the other parts of the diorite, and the rock as a whole is markedly poorer in granitic interstitial material. It seems likely that the feldspar component of this granitic material has gone to form the alkali feldspar rims to the plagioclase phenocrysts; the rims of these phenocrysts are often seen to be contiguous and only a few scattered quartz-alkali feldspar intergrowths were found in this rock.

The clinopyroxene crystals in this rock show similar form and size to those present in the marginal diorite, and they are sometimes seen to be partly moulded on to the feldspar and ore grains in the rock but are commonly independent of these other crystals; these clinopyroxene crystals are of a pale green colour which contrasts with the pale brown colour of those present in the diorite wall-rock and may indicate that they are richer in iron than the augites in the main facies of the diorite. No determinations of the composition of these pale green clinopyroxene crystals were made; many of these pyroxene grains are partly or wholly replaced by homoaxial growths of pale brown pleochroic clinoamphibole.

Ore occurs in this rock as small equant sections which contrast with the often elongated form of the ore grains in the other diorite types. The schliere rock was found to contain occasional grains of olivine; this mineral forms large subhedral to anhedral areas up to 5 mm. in width which were usually found to be pseudomorphed by brown fibrous alteration products, and these crystals commonly enclose the smaller plagioclase phenocrysts in poikilophitic textures very similar to those described from the Upper Zone (UZ) of the Layered Series of the Skaergaard Intrusion (Wager and Deer 1939; Wager and Brown 1968) (see Fig. 73), and the Shiant Sill (Johnston 1953). The exact form of the individual olivine crystals in these pseudomorph areas is difficult to determine.

The plagioclases enclosed by the olivine crystals have the rapidly

Fig. 73



Rock from a small schliere in the diorite of southwestern Urdarfell, showing small plagioclase, pyroxene and ore crystals set in a fine-grained acid matrix similar to that of the marginal diorite (see Fig. 70). A large aggregate of honey-coloured fibrous pseudomorphs after olivine can be seen in the centre of the field.

Plane-polarized light, x 15 (Specimen Vi 399).

zoned rims characteristic of the plagioclases in the other hybrid rocks, but none were seen to have the broad cloudy rims developed in these other plagioclases. In addition, these olivine grains enclose small fresh pale green clinopyroxene grains; the balance of evidence is taken to indicate that olivine crystallized after the plagioclase phenocrysts and at or towards the end of the period of pyroxene crystallization in this rock. Although the olivine is too highly altered for its composition to be determined, it seems possible that it is an iron-rich type, as it crystallized later than the outermost sodic oligoclase zones of the plagioclase phenocrysts; in the Skaergaard UZ rocks, the olivine crystallizing from a liquid precipitating plagioclase in the range An_{45} to An_{30} was found to have a composition in the range Fa_{60} to Fa_{100}, and the later-formed zones of the Shiant olivines crystallizing from a liquid precipitating An_{35} plagioclase were found to have compositions up to Fa_{90} (Wager and Deer, op. cit.; Johnston, op. cit.; Wager and Brown, op. cit.). No olivine was found in the Slaufrudal hybrid rocks (Beswick 1965).

The margins of these schlieren and patches of olivine-bearing rock are sharp in hand-specimens, but were not seen to be so in thin sections of the rock; and this is taken to evidence that the schlieren formed within the main diorite before this had fully cooled.

The texture of those parts of both the marginal and main facies diorite remote from the earlier acid rocks (and presumably not mixed with these acid rocks) has a distinctly hybrid appearance, with corroded crystals of relatively basic minerals (labradorite-andesine and magnesian augite) set in a felsitic or graphic quartz-alkali feldspar matrix (see Figs. 70, 71a, 72). The fact that these basic and acid constituents can be readily distinguished in thin section reflects the essentially mechanical mixing process by which the diorite was formed and the two diorite types are felt to embody the principle suggested by Holmes and Harwood (1928, p. 511): "If the two magmas (acid and basic) . . . were . . . mixed together at not too high temperatures, they would still to a certain extent preserve their individualities, and either separate out by crystallization or otherwise, or give rise to a hybrid series of rocks."

2. Fine-Grained Hybrid Rocks (H_F)

These rocks have textural and mineralogical features of both the Urdarfell felsite and diorite types, and they show some variation in texture; the main characteristics of the rocks, however, are sufficiently distinctive for them to be recognized as a distinct type.

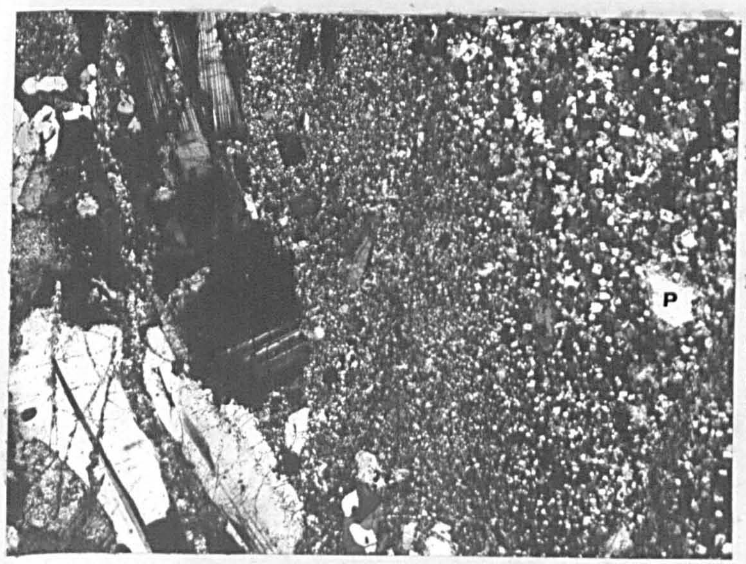
Zoned andesine-oligoclase plagioclase phenocrysts of the type seen in the marginal facies of the diorite are scattered through the rock; these have clear cores and cloudy sodic rims which may be slightly corroded. A few phenocrysts of pale green augite are also present; these show elongated forms up to about 1 mm. in length and were usually found to show ragged outlines. Phenocrysts are not abundant in these fine-grained hybrids.

The groundmass of the rock is a fine-grained granular fabric of clear quartz and cloudy alkali feldspar grains of felsitic to microgranitic texture and is similar to that seen in the interstices of the diorite types, showing a pale pink-brown colour in ordinary light (see Fig. 74).

Small ore grains showing subhedral square sections were also found in the fine-grained groundmass, and some of these enclose small sphene grains; a few scattered euhedral elongated crystals of apatite and zircon were also seen in this rock.

Parts of this fine-grained hybrid rock were found to show a very uniform granular texture in which the groundmass ore, quartz and alkali

Fig. 74



The margin of a fine-grained felsitic hybrid vein (H_F), from southwestern Urdarfell, showing a strongly-chilled margin against main facies diorite. A small clear labradorite-andesine phenocryst (P) is seen to rest in a fine-grained felsitic to micrographitic groundmass which contains scattered small grains of ore. No clinopyroxene phenocrysts are seen in this part of the field.

Cross-polarized light, x 15 (Specimen Vi 392b).

feldspar grains are seen as tightly interlocking equant blebs; the feldspar in these parts of the rock is exceptionally clear and unclouded, and the quartz grains in the occasional graphic frets seen in the rock have more rounded outlines than those seen in the other parts of the groundmass. The zoned andesine oligoclase phenocrysts in this rock were often found to show considerable marginal embayment due to corrosion, and the pale brown amphibole rims to the pyroxene grains are much broader than those which occur elsewhere in the H_F rocks; amphibole may make up to 90 per cent by volume of these grains. The general appearance of these localized granular patches in the rock is suggestive of recrystallization accompanied by some reaction between the relatively calcic plagioclase and augite crystals and the acid interstitial material which surrounds them. It seems likely that this recrystallization and reaction resulted from partial fusion of the H_F rock, and the heat source for this process may have been the later part of the main facies diorite or the later Urdarfell gabbro tongue which outcrops 100-200 m. south of the H_F outcrops; this process is believed to have operated after the formation of most of the H_F rock.

Medium-dark grey veins of the fine-grained hybrid rock were found to be common within the main facies of the diorite and these show sharply chilled margins which rest against the truncated ends of crystals in this rock (see Figs.74 and 37); these veins show similar mineralogy and granular texture to the fine-grained rocks described above and contain cloudy feldspar grains. It seems likely that these veins are portions of remelted marginal H_F material of the same origin as the granular patches.

The truncated ends of the pale brown augites in the main facies diorite were found to show a narrow optically continuous zone of pale green clinopyroxene adjacent to the vein contacts which suggests that some reaction with exchange of iron and magnesium took place at these interfaces.

Similar veins of dark fine-grained hybrid material have been described from the Slaufrudal stock by Beswick (1965).

3. Coarse-Grained Hybrid Rocks

The more acid hybrids are described first, in order to demonstrate the sharp contrast between the two end members of the hybrid series and also to show that the intermediate hybrid rocks have textural and mineralogical features characteristic of each of these end members.

(a) Granite (H_G)

This rock is classed as a hybrid rock because it was found to contain xenocrystic plagioclases similar to those found in the diorite (or labradorite-andesine cumulate). It is termed a granite as it shows a well-developed equigranular texture and is not miarolitic (Wager *et al.* 1965; Beswick 1965).

The mode of the rock was found to be:

Plagioclase (mostly as xenocrysts)	7.2
Ferromagnesian silicates	3.9
Ore	2.3
Alkali feldspar	56.5
Quartz	28.9
Accessory minerals (sphene, zircon, apatite, allanite, etc.)	1.2

The rock contains scattered euhedral elongated plagioclase crystals of the same order of size as those seen in the diorite and these crystals have clear cores showing the same zoning range as those in the diorite; their outer zones pass into a broad rim of cloudy feldspar which may make up to 50 per cent of the crystal width (see Fig. 75).

Fig. 75

Granitic rock (H_G) from the lowest levels of the section in the southern Urdarfell fault gully wall. A large near-equidimensional cross-section of a plagioclase xenocryst can be seen near the centre of the field and this has a broad rim of finely-twinned alkali feldspar; the centre of this crystal is missing. The rest of the field is occupied by large, often equant grains of clear quartz and cloudy or finely-twinned alkali feldspar which may be intergrown in graphic textures of widely varying fret size; a glomerogranular quartz-alkali feldspar cluster is seen in the upper left corner of the field.

Cross-polarized light, x 15 (Specimen Vi 615).

These cloudy sodic rims are invariably mantled by discontinuous rims of alkali feldspar which are intergrown in graphic textures with quartz. The alkali feldspar in this rock occurs as large anhedral grains often of equant form and up to about 1 mm. in size; closely-spaced lamellar twinning parallel to (010) appears to be more abundant in those parts of the alkali feldspar forming rims to the plagioclase xenocrysts and this material was found to have a composition approaching that of albite (An_0 to An_5). Some of these extremely sodic rims were seen to show faint cross-hatched twinning which may indicate that they are anorthoclase types. Other parts of the granite within the area of a single thin section may contain feldspar grains of cloudy appearance which are often untwinned but sometimes twinned on the Carlsbad law; this cloudiness appears to be due to the presence of numerous small dust-like particles but may be partly due to the unmixing of a more potassic alkali feldspar. These cloudy grains do not appear to grade into the graphic rims of the andesine xenocryst plagioclases, and are associated in granular clusters with equant quartz grains (see Fig. 75). These quartz-feldspar clusters are similar in texture to the glomerogranular aggregates of the same minerals described by Hawkes (1929) and Beswick (1965) from the acid intrusions of eastern Iceland; these authors interpret such clusters as the solid portions of a largely mobile acid magma. Their presence in the H_G granitic hybrid is felt to be due to part consolidation of the original acid material before mixing with the diorite to form the hybrid rocks.

Quartz forms about 29 per cent of the rock, and is seen as clear anhedral grains up to 1 mm. in size which may be of equant or elongated form; these grains are mostly seen to form graphic intergrowths of very variable fret size which are rarely seen to be as regular as those of the MU granophyre (see Figs. 69a and 69b).

A pale green clinopyroxene similar in appearance to the type seen in the fine-grained hybrids and the acid minor intrusions forms about 3-4 per cent of the rock by volume and is seen as short subhedral prisms up to 1.2 x 0.5 mm. in size; the composition of this mineral is estimated to be approximately $(Ca + Mg)_{72-79}Fe_{21-28}$ which is a relatively iron-poor augite to occur in a granitic rock. No exsolution textures were found in this augite, and the grains often enclose small equant ore grains up to 0.2 mm. in size.

Many of the clinopyroxene grains are mantled by homoaxial growths of pleochroic clinoamphibole, which makes determination of their optical properties difficult; this amphibole shows absorption colours which range from a bright green which may have a faint bluish tinge to a pale brown colour and its optical properties suggest that it is a hornblende. The amphibole is felt to be deuteric, as small crystals of exactly similar material were found in the final interstices of the granite.

Opaque ore occurs as small ragged grains up to 1 mm. in length, the smaller of which may be enclosed by the clinopyroxene crystals; this is felt to suggest that the mineral is of early crystallization in this rock.

Small euhedral rods of apatite and pale pink zircon are scattered throughout the rock, together with a few small pink sphene grains which are sometimes seen to be enclosed by the ore grains; this indicates that sphene crystallized at an early stage in the cooling history of the rock. A small number of pale yellow epidote prisms were seen in the granite, and a few of these were found to form homoaxial overgrowths to small golden-brown allanite prisms.

The final gaps in the fabric are seen as widely scattered small cavities up to 1.5 mm. in width which are not nearly so abundant as the miarolitic cavities found in the MU granophyre and were not found to contain crystals of quartz or epidote. These cavities in the granite contain sheaves of small acicular crystals of clear bright green clinoamphiboles showing similar optical properties to those found to mantle the clinopyroxenes; these needles are up to about 0.5 mm. in length with a length to breadth ratio of 12:1.

A few small rounded inclusions of more basic fine-grained rock were found to be scattered throughout the granite; these range up to about 1 cm. in diameter and were found to be of a rock type similar to that of the marginal facies of the diorite, with brown amphibole, opaque ore and plagioclase laths sometimes arranged in stellate clusters. No sharp margins were seen to exist between these inclusions and the surrounding granite, and they are felt to be small parts of the marginal diorite which broke away from the main mass while this was still unconsolidated and moving through the granitic material.

(b) Basic Granophyre (H_I)

As has already been mentioned, this rock shows textural and mineralogical features of both diorite and granite, which can only be explained by physical mixing of these two types while they were still mobile. Some variation in texture was seen in this rock, but the general texture of the rock is sufficiently uniform for it to be recognized as a distinct rock type in thin section and hand specimen. The mode of the rock was found to be:

Plagioclase	38.6
Clinopyroxene	7.5
Amphibole and chlorite	1.0
Ore	4.3

Accessory/...

Accessory minerals (sphene, apatite, zircon)	0.4
Graphic material	48.2

The rock is poorer in plagioclase and clinopyroxene but richer in graphic material than the diorite.

Large euhedral columnar crystals of plagioclase in a high-temperature to intermediate structural state make up nearly 40 per cent of this rock and these are twinned on albite, Carlsbad and pericline laws; these crystals have clear cores of andesine (An_{46}) with narrow rims showing continuous zoning from about An_{40} to An_{14} within a distance of about 10-20 per cent of the total crystal width (see Fig. 76). The more sodic plagioclase of the outermost rim zones was often found to show slight cloudiness and to be corroded, showing an

Fig. 76

Basic hybrid granophyre from the H_I zone of the north wall of the southern Urdarfell fault gully (see Fig. 36). Large euhedral plagioclase crystals with cores of andesine zoned to sodic oligoclase are clearly seen, and an elongated augite crystal (A) containing some small ore grains lies across the lower part of the field; a triangular area of medium-fret quartz-alkali feldspar intergrowth is seen between this augite crystal and the sharply-defined edge of an adjacent plagioclase crystal. A glomerogranular quartz-alkali feldspar cluster lies just left of the centre of the field.

Cross-polarized light, x 15 (Specimen Vi 265/14).

irregularly-shaped border, as was also seen to be the case in the plagioclase phenocrysts in the diorite (see Fig. 72). The corroded rims in the H_I rock are mantled by discontinuous overgrowths of cloudy alkali feldspar which pass outwards into graphic intergrowth with clear quartz grains.

The clinopyroxene in this rock was found to be a pale pink-brown calcic augite ($Ca_{40.5}Mg_{39}Fe_{20.5}$, No. 4, Fig. 90), which commonly forms acicular subhedral crystals up to 6 mm. in length along the c-axis with a length to breadth ratio of up to 8:1; this pyroxene often partly or wholly encloses small equant ore grains (see Fig. 76). A number of pyroxene grains were seen to contain numerous minute dust-like ore particles but these showed no apparent zonal distribution of the type seen in the Hôlar marginal dolerite augite phenocrysts (see Fig. 55). Some of the augite grains in the samples of H_I rock examined showed distinct continuous exsolution lamellae parallel to (001); these lamellae are of material with low birefringence which is taken to be exsolved pigeonite (Brown 1957; Bown and Gay 1960). No discrete crystals of pigeonite were found in these H_I rocks.

All of the pyroxene crystals in the H_I rocks were found to have homoaxial rims of pleochroic clinoamphibole showing absorption colours ranging from a grass-green to a very pale brown colour; the size of these rims shows some variation, but this was not investigated in detail; and the phenomenon appears to be of ubiquitous occurrence within the diorite-H_I-H_G series.

As in the H_G rocks, the development of amphibole appears to have taken place during the later stages of crystallization of the rock; numerous pyroxene grains were found to be almost completely pseudomorphed by amphibole, and the mineral was also found as discrete crystals of smaller size than the pyroxene crystals and as very small acicular crystals in the final gaps in the fabric. Some of the larger amphibole grains were found to show zoning from grass-green cores to narrow rims of pale blue-green chlorite.

Ore forms about 4 per cent of the rock, and occurs either as euhedral skeletal crystals of elongated form up to 3 mm. in length or as smaller euhedral polygonal sections up to 1.5 mm. in width. Many of the smallest grains were found to be partly or wholly enclosed by pyroxene crystals (see Fig. 76) and these are presumably of early precipitation; some of the larger grains were seen to be partly moulded on to pyroxene grains which suggests that the period of ore crystallization in the H_I rock ended after that of the pyroxene.

Some of the ore grains were seen to be moulded on crystals of sphene; this mineral occurs as small euhedral oblong sections up to 0.1 mm. in length or as larger grains of amoeboid form up to 1 mm. in width. The frequently observed enclosure of sphene crystals by ore grains indicates that sphene formed at an early stage in the crystallization of the H_I rock.

Apatite rods up to 2 mm. in length with a length to breadth ratio of 25-30:1 are more abundant in the H_I rock than in the two end-member rocks and appear to be especially abundant in the gaps between the plagioclase and pyroxene crystals; these crystals are sometimes seen to be enclosed by ore and pyroxene crystals and often show euhedral hexagonal cross-sections. Small elongated zircon crystals of a very pale pink colour also occur in the rock.

The bulk of the space between the plagioclase, pyroxene and ore crystals is filled by intergrowths of quartz and alkali feldspar of two types distinguished by their grain size; the fine-grained types are micrographic intergrowths of fine to medium fret size and the coarsest types are glomerogranular aggregates comparable in size to those of the H_G rock (see Figs. 75 and 76). The fret types found within the H_I rocks were all of more regular form than those seen in the H_G rocks, but were rarely seen to form complete mantles to the plagioclase phenocrysts as do those in the MU granophyre; in addition, the H_I and H_G intergrowths were found to form discontinuous mantles to the plagioclase phenocrysts, in contrast to the continuous mantles observed in the phenocrysts of the MU granophyre. The discontinuous nature of the graphic mantles and the corroded rims of the large plagioclase crystals in the hybrid rocks are taken to indicate that these crystals are true xenocrysts which were not in equilibrium with the more acid material into which they were introduced with the result that some resorption and reaction occurred at their margins before the final solidification of the granitic host liquid as interstitial graphic material.

The composition of the pyroxene crystals in the H_I rock is almost identical to that of the augites of the Hólar dolerite margin and the Urdarfell gabbro, both of which are in equilibrium with liquids precipitating plagioclase in the compositional range An_{60} to An_{50}. The widespread occurrence of amphibole rims is taken to evidence that considerable reaction took place between the gabbroic augite and the granitic liquid into which it was introduced; the only augite grains found to be free of amphibole were those totally enclosed by large plagioclase crystals, which presumably insulated these augites from reaction with the granitic liquid. The replacement of augite by an amphibole in these Urdarfell rocks is a similar phenomenon to that observed in other examples of reaction between ferromagnesian minerals and interstitial liquid in the Caledonian Igneous Province of Scotland, notably the Cairnsmore of Carsphairn complex (Deer 1935).

3-8: THE URDARFELL GABBRO TONGUE

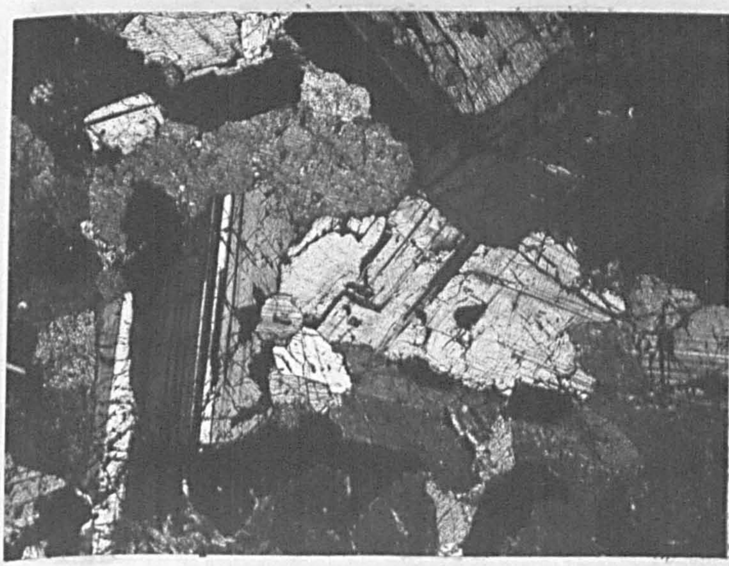
This rock is very similar in texture and mineralogy to the pegmatitic gabbro described from the Hólar-Skessusaeti intrusion with dark minerals making up over half of the rock by volume, but shows coarser grain size than any of these types (see Fig. 77). The mode of the rock was found to be:

Plagioclase	45.7
Clinopyroxene	34.8
Amphibole	3.8
Ore	13.0
Accessory minerals and interstitial material	2.7

The plagioclase in the Urdarfell gabbro occurs as large elongated crystals of almost euhedral prismatic form, which are commonly 15 x 3 mm. in size and are twinned on albite, Albite-Carlsbad, Carlsbad and pericline laws; these crystals were found to have cores of high-temperature labradorite in the range An_{65} to An_{56} which are zoned to narrow rims of andesine (An_{44}) which were rarely seen to make up more than 10 per cent of the crystal width. The cores of a few of these large plagioclase crystals were found to contain scattered inclusions of ore and ferromagnesian material; and many of the crystals in the marginal parts of the intrusion were seen to be crushed and fractured, which is taken to indicate that these crystals were of large size at the time of emplacement of the intrusion. The clinopyroxene in this rock is a pale pink-brown calcic augite which forms large anhedral grains commonly 10 x 10 mm. in area which are interstitial to the largest plagioclase crystals and may enclose the smallest grains in poikilophitic intergrowth; the composition of this clinopyroxene was determined as $Ca_{40}Mg_{39}Fe_{21}$ (No. 5, Fig. 90), and this is similar to the compositions of the augites in the Hólar-Skessusaeti marginal dolerite and the H_I rock.

No exsolution or inversion textures were found in these augite crystals but a large number were found to contain small rods of opaque ore aligned parallel to the (001) and (110) cleavages. Occasional pyroxene grains were seen to bear a rim of pleochroic amphibole identical to that seen at pyroxene margins in the diorite and H_I rock, and these appear to be most abundant in those parts of the gabbro which were found to include small patches of the hybrid rock.

Fig. 77



The Urdarfell gabbro, showing large subhedral crystals of labradorite plagioclase surrounded by large anhedral grains of augite. Some interstitial ore is also present.

Cross-polarized light, x 15 (Specimen Vi 265/8).

Small patches of red-brown biotite were found at the margins of some of the pyroxene grains.

Ore occurs in the gabbro as large grains of amoeboid form up to about 6 mm. in width which are moulded on to the feldspar and pyroxene grains, and also as smaller subhedral polygonal grains typically about 1 mm. in size which are often seen to be enclosed by the pyroxene grains; the presence of these two ore habits is taken as evidence that precipitation of ore from the gabbro liquid began before that of pyroxene and continued after the end of the period of pyroxene precipitation.

Some variation in grain size was seen in the gabbro and a coarser gabbro type was seen in small lenticles parallel to and near the lower contact of the tongue; in these the plagioclase layers commonly reach lengths of 20-30 mm. (exceptionally 70 mm.) and the pyroxenes may be up to 40 x 40 mm. in size. These layers are felt to represent the crystallization products of a liquid supersaturated with respect to pyroxene by analogy with the wavy-pyroxene rock described from the Tranquil Division of the Skaergaard Marginal Border Group (Wager and Deer 1939; Wager and Brown 1968, Figs. 78 and 79) and are identical in appearance to the pegmatitic gabbros forming the latest-emplaced units of the Hólar-Skessusaeti intrusion; the similar mineralogy and texture of the Urdarfell and Hólar-Skessusaeti gabbros and the field evidence of their contemporaneous injection may indicate that they were formed from similar liquid fractions of a large differentiating basic body beneath Vididalsfjall. The plagioclase in the pegmatitic coarse-grained parts of the Urdarfell gabbro was found to show the same compositional range as that in the main part of the intrusion. The small patch of gabbro found just north of Selfell is similar in type to the Urdarfell rock and is felt to be of common origin to this rock.

Two other textural features of the Urdarfell gabbro tongue are of interest.

Small patches of diorite or H_I material up to about 5 cm. in width were found to be of common occurrence in the lower part of the intrusion; these hybrid patches are readily distinguished in thin section by their strikingly zoned plagioclase phenocrysts, elongated clinopyroxene phenocrysts, abundant apatite rods and occasional zircon and sphene crystals. Crystals of apatite, zircon and sphene were not found within the main body of the gabbro as products of primary crystallization, but were only seen in these hybrid patches; occasional small "stringers" of micrographic material were seen to pass from the hybrid patches into the gaps of the gabbro mesh over distances up to a few millimetres, and the rims of the gabbro augites contiguous with these patches were found to be altered to pleochroic amphibole of the same type as that seen in the diorite and H_I rocks. These textures are felt to indicate that the gabbro entrained small loose crystal clusters of the diorite or H_I material before this had fully consolidated. No evidence of further hybridization between the gabbro and intermediate rock types was found, and this is believed to be further evidence that the gabbro was in an advanced state of crystallization by the time it was injected into its present position; however, the gabbro peripheral to these inclusions often shows marked coarsening in grain size and these coarse patches are only distinguishable from the pegmatitic gabbro by the presence of the central hybrid rock inclusion. Similar coarse-grained patches have been found to surround inclusions of hybrid material in the Vesturhorn gabbros (J. Roobol, pers. comm., 1967) and the same phenomenon has been described from the Skaergaard Marginal Border Group gabbros where these include acid material (Wager and Deer 1939; Wager and Brown 1968, Fig. 86).

The pale anorthositic facies of the gabbro seen at the 520 m. level on eastern Urdarfell was found to show the same mineralogy as the more melanocratic gabbro in the rest of the outcrop, and contains about 75 per cent by volume of large labradorite crystals, with very small amounts of interstitial augite and ore. Small patches of hybrid rock similar to those seen in the darker gabbro were also found in this rock, and these show the same textural relationships to the pale gabbro as those found elsewhere in the gabbro, so that they are considered to be small included crystal clusters of hybrid material.

The pale gabbro itself shows the textures typical of a plagioclase orthocumulate, and bears labradorite crystals which were not found to differ in any way from those in the darker gabbro; the few small patches of the pale gabbro found appeared to be continuous with the darker gabbro and are interpreted as small parts of the original plagioclase orthocumulate from which the pyroxene-precipitating intercumulus liquid was squeezed, either during injection of the gabbro or shortly after emplacement. These small patches of pale gabbro appear to be concentrated near the lower margin of the intrusion so that the squeezing-out of the intercumulus liquid may have been caused by rolling of bundles of phenocrysts along the floor of the space occupied by the gabbro. Evidence for the injection of the gabbro as a plagioclase cumulate is given by the fracturing of large crystals observed near the margins of the intrusion and in the thin veins which proceed from it, which implies some transport of the plagioclase phenocrysts. The abundance of large plagioclase phenocrysts in the thin gabbro veins which cut the tuffs near the contacts of the tongue also testifies to the advanced state of crystallization of the plagioclase at the time of injection of the gabbro. Indirect evidence of the existence of labradorite plagioclase cumulates is given by the occurrence, already noted, of loose crystal clusters of plagioclase in some of the early basic cone-sheets (see Fig. 59b); the formation of these cumulates in depth would have taken place some time before the injection of the Urdarfell gabbro but in view of the apparently rapid sequence of emplacement observed in Vididalsfjall it seems possible that cumulates of this period may have been injected at higher levels to form the Urdarfell gabbro.

A few small inclusions (less than 5 cm. in diameter) of eucrite and Type 1 early-set cone-sheet material were also found in the gabbro; these and the H_I inclusions have already been mentioned (p.231).

No other variations in the texture of the gabbro were found apart from the development of a basal 2-5 cm. zone of noticeably finer-grained rock in which the plagioclases are only up to about 1 mm. in length and are often seen to be in sub-ophitic intergrowth with the augite grains.

This zone is interpreted as the lower chilled margin of the intrusion; its thinness and lack of extreme fine grain are believed to show that the gabbro was intruded into hot hybrid rocks; similar "hot rock" contacts between gabbro and hybrid intrusions have been observed in the Vesturhorn intrusive complex of eastern Iceland (J. Roobol, pers. comm., 1967).

3-9: ACID VEINS

A few acid veins were found to cut the Dalsá-Urdarfell felsite intrusion, the hybrid rocks and the gabbro on Urdarfell; the samples examined fall into two main types which were found to show different mineralogy, and different contact relationships to their wall-rock. Both these types are distinguished from the MU granophyre by their equigranular granitic texture.

Type 1

Only one vein of this type was found; this vein was not seen to show chilled or fine-grained contacts against the H_I rock and gabbro into which it was injected, and this is taken to suggest that it was injected into hot rock. This vein has undergone more hydrothermal alteration than the Type 2 veins, and may be of earlier injection than these types.

The vein is similar in mineralogy and texture to the HG granitic rock, but was not seen to be connected to this mass, and is a more or less equigranular fabric of cloudy feldspar and interstitial quartz in which the feldspar shows similar appearance to the much-twinned albitic plagioclase seen in the H_G rock. No graphic intergrowths between quartz and feldspar were found in this rock, and scattered acicular crystals of green amphibole showing a similar pleochroism scheme to that of the amphibole in the H_I and H_G rocks are present, together with small ragged grains of ore. A few small subhedral grains of pale pink sphene were also found in the rock, and also some scattered rods of apatite and pinkish zircon. Some small rods of yellow epidote and patches of carbonate were also seen in the rock.

Along parts of the contact with the Urdarfell gabbro, the vein material has apparently reacted with the pyroxene to form a narrow zone of amphibole and this is often seen to be chloritized; the gabbro feldspar also appears to have undergone some chemical change, which may be albitization, but the contacts in the specimens examined were not fresh enough to ascertain the exact nature of this change. The alteration of the wall-rock, however, is taken to be further evidence of its high temperature at the time of injection by the vein.

Type 2

Most of the Type 2 veins examined were found to show felsitic chilled contacts against their wall-rock, which indicates that they were injected into cold rock (see Fig. 78). These veins are composed predominantly of equant grains of clear quartz and slightly cloudy

Fig. 78

The contact of a Type 2 acid vein and H_I rock in the north wall of the southern Urdarfell fault gully, showing the sharp fine-grained vein margin resting against apparently unaltered truncated crystals of the wall-rock near the right border of the field.

Cross-polarized light, x 15 (Specimen Vi 214).

alkali feldspar which form an equigranular granitic fabric; some of the quartz and feldspar grains were seen to be intergrown in medium-coarse-fret graphic intergrowths in each of the samples examined, but such intergrowths were not found to be abundant. Some of the intergrowth areas are up to about 2 x 2 mm. in area, and in one example intergrowths of this size were found to be concentrated along the contact.

The mode of a Type 2 acid vein from southern Urdarfell was found to be:

Alkali feldspar		60.8
Quartz:	granular	35.7
	phenocrysts	0.1
Ferromagnesian silicates Ore, carbonate Sphene, zircon and apatite		0.8
Graphic material		2.6

One vein was found to contain three types of quartz characterized by different habits. The bulk of the quartz in the rock forms either ragged anhedral equant grains interstitial to the alkali feldspar or subhedral wedge-forms in graphic intergrowth with the feldspar. The third type of quartz forms small euhedral to subhedral square sections which may show skeletal forms, and these crystals were usually found to be enclosed by the graphic intergrowths and to show different extinction positions to those of the quartz units in the graphic material; crystals of this third type were usually found to be much less abundant than the other two types, and to range up to 0.5-1.0 mm. in size. A few very small crystals of this type were found at the centres of graphic intergrowths in similar fashion to the quartz phenocrysts at spherulite centres in the MU granophyre (see Fig. 66b), and by analogy with these types they are believed to be phenocrysts of β-quartz showing characteristic bipyramidal form; the textural relationships of these phenocrysts in the vein rock are felt to indicate that these quartzes were of early precipitation.

The alkali feldspar in these veins appears to be a micro- to cryptoperthitic type and was usually seen to be cloudy; this is probably due to some unmixing of the feldspar, which was found to be an anorthoclase type. The feldspar in these veins was seen to show only simple twinning on the Carlsbad law, and no crystals were found to consist of more than two twin individuals; many of the crystals were seen to pass continuously into graphic intergrowth with quartz. No plagioclase was found in these veins.

Ferromagnesian minerals appear to be very rare in the examples of these veins examined, but scattered small grains of green-brown clinoamphibole and red-brown biotite were found in one example from the eastern side of Urdarfell; this vein shows less marked decrease in grain size against its basalt wall rock, and appears to have reacted with this rock to form blades of red-brown biotite and amphibole near the contacts.

A few small ragged ore grains were found in each of the veins examined, as also were a few small grains of pale pink sphene and darker pink to pale brown zircon with ragged outlines which contrast with their more commonly euhedral form; small prisms of yellow epidote were found in most of the veins and rare crystals of brown allanite were found in one vein. The final gaps in the fabric are usually occupied by carbonate.

Origin of the Acid Veins

A detailed analysis of the origin of the acid veins has not been attempted, but they show very similar characters to the acid veins found in the intrusive complexes of Slaufrudal (Beswick 1965), Austurhorn (Blake 1966) and Vesturhorn (Roobol, pers. comm., 1967) in eastern Iceland, and to the veins seen in the Coire Dubh area of Rhum (Dunham 1964). The veins described in the literature cited are believed to have been formed by the remelting of acid material by hotter basic intrusions and the subsequent injection of this remobilized material into fissures in the surrounding rocks; these veins are sometimes found to inject the material which caused their remobilization, to produce the phenomenon known as "back-veining", which is becoming increasingly more widely recognized as being the mechanism whereby late-stage acid veins, originally thought to be the more acid differentiates of acid bodies, were formed.

The Type 1 vein seen to cut the H_I rock and the Urdarfell gabbro may be H_G material which was remobilized by the intruding gabbro and back-veined it; no other likely source of heat capable of remobilizing the acid rock was found in the rocks belonging to this part of the intrusive sequence on Urdarfell, and the vein shows a similar degree of hydrothermal alteration to the gabbro and hybrid rocks which provides a rough guide to its age.

The Type 2 veins show almost no hydrothermal alteration and were usually found to show sharply chilled fine-grained margins against their wall-rock; this is taken to indicate that they were emplaced at a later date than the Type 1 vein, as the hybrid rocks had probably cooled considerably by this time. No obvious likely heat source capable of producing such veins from the acid intrusions of the central zone was found exposed; if these veins are in fact due to the remobilization of the Urdarfell (or related) intrusions, it is tentatively suggested that this remelting was due to heating by hidden basic intrusions of the Second Phase of the intrusive sequence.

B. THE SECOND PHASE ROCKS

3-10: LATE BASIC CONE-SHEETS AND RELATED INTRUSIONS

As in the early basic cone-sheets, the dolerite of the late basic cone-sheets shows great uniformity of texture within each of three main types. All but two of the 31 thin sections of late-set sheets examined were found to bear olivine and these two exceptional sheets are extremely fine-grained.

Type 1

Sheets of this type are porphyritic olivine-tholeiites bearing phenocrysts of plagioclase, clinopyroxene and olivine; the grain size of the groundmass in these sheets was found to vary between different sheets, but remained constant within individual sheets. The proportion of plagioclase phenocrysts present in the sheets was found to range up to about 20 per cent by volume.

The mode of a Type 1 sheet from Ásmundarnúpur was found to be:

Phenocrysts:	Plagioclase	9.7
Groundmass:	Plagioclase	48.6
	Clinopyroxene	25.3
	Olivine	6.5
	Ore	6.2
	Interstitial material and accessory minerals	3.7

The Phenocrysts

Euhedral phenocrysts of plagioclase, clinopyroxene, olivine and rare ore were found in the Type 1 sheets up to a short distance from the contacts, and as in the early-set Type 1 sheets, the number of these crystals was found to increase inwards from the contacts.

The plagioclase phenocrysts range up to 5 mm. in greatest length, and show stumpy to tabular form, with some flattening parallel to (010); many of the cores of crystals examined were found to bear numerous small inclusions of ore and ferromagnesian material alighed parallel with the cleavages; some of these inclusions were seen to have rectilinear outlines, while others showed bleb-like form. The crystals are twinned mainly on albite, Albite-Carlsbad, Carlsbad and pericline laws, and have cores of bytownite in the range An_{90} to An_{80}, which commonly make up to 60 per cent of the volume of the crystal; these cores are succeeded by a mantle which is zoned normally but generally with some discontinuity to compositions as sodic as andesine (An_{40} to An_{32}). (See Fig. 79a.)

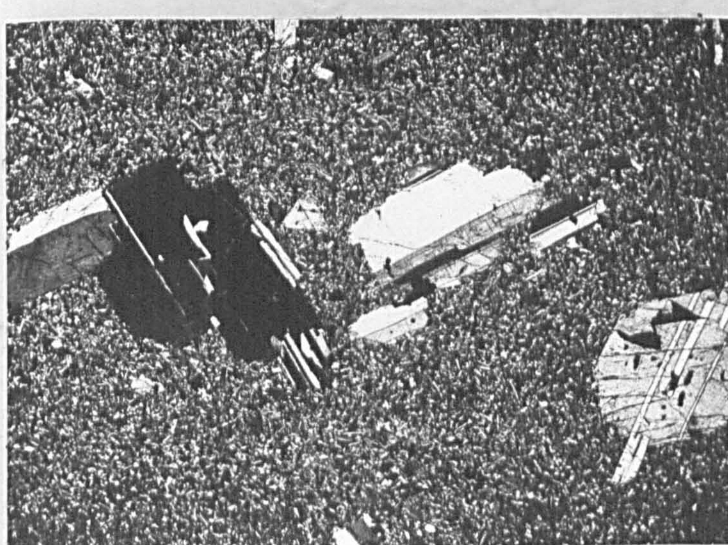
The widest part of the zoned mantle to the core was found to lie in the compositional range An_{70} to An_{50}, and to be of high-temperature plagioclase. The most sodic outer parts of this mantle were often seen to enclose small groundmass crystals of pyroxene, olivine, plagioclase and ore. A few euhedral to subhedral phenocrysts of forsteritic olivine (Fa_{20-26}) were found in the marginal facies of most of the sheets examined; these crystals show sections up to 1.5 x 1.0 mm. in

Fig. 79a

A Type 1 late-set cone-sheet from the 400 m. level on western Ásmundarnúpur, showing a cluster of large plagioclase phenocrysts; one of these crystals shows a distinct mantle zoned from bytownite to andesine. The outer part of this mantle partly encloses small groundmass crystals of pyroxene and plagioclase. The groundmass of the rock contains small anhedral olivine crystals (O) and interstitial opaque ore grains.

Cross-polarized light, x 15 (Specimen Vi 320).

Fig. 79b



A Type 1 late-set cone-sheet from western Ásmundarnúpur, showing similar plagioclase phenocrysts to those in Fig. 79a, set in a finer-grained groundmass of olivine, pyroxene, plagioclase and ore.

Cross-polarized light, x 15 (Specimen Vi 304).

size, and were often found to be partly pseudomorphed by serpentinous material , ore and carbonate. None of the olivine phenocrysts found in these rocks showed perfectly euhedral form in section, and although many showed well-developed crystal faces, all showed a slight rounding at apices and the margins of many crystals were seen to enclose the tips of groundmass feldspars in subophitic intergrowth. This is taken to indicate that the liquid caused some resorption and reaction of these crystals.

Clinopyroxene phenocrysts were found to be apparently less abundant than crystals of plagioclase or olivine but subhedral crystals of pale pink-brown calcic augite often twinned parallel to (100) were found in most of the sheets examined; no exsolution textures were found in these crystals, which occur as single crystals or in glomero-porphyritic clusters with the plagioclase phenocrysts in the same fashion as the olivine crystals. In some rocks all three minerals were found to occur together in clusters; in these cases olivine and plagioclase appear to have crystallized almost simultaneously before the pyroxene, which was seen to be moulded on to crystals of these two minerals. Some of the pyroxene phenocrysts examined were found to show a rim of near-uniaxial material, and this is taken to represent pigeonite; no optical discontinuity was seen between the core and rim in these examples; the calcic augite of the cores was found to have a composition of $Ca_{39.5}Mg_{37.5-39}Fe_{21.5-23}$ (Nos. 6 and 9, Fig. 90).

Few ore phenocrysts were found in the marginal facies of the

Type 1 sheets and this is taken to indicate that most of the sheets examined were intruded before the magma had started to precipitate this mineral. Most of the sheets appear to have been intruded at a time when the magma had started to precipitate augite and the crystallization of plagioclase and olivine was already far advanced, as evidenced by the size of phenocrysts of these minerals.

The Groundmass

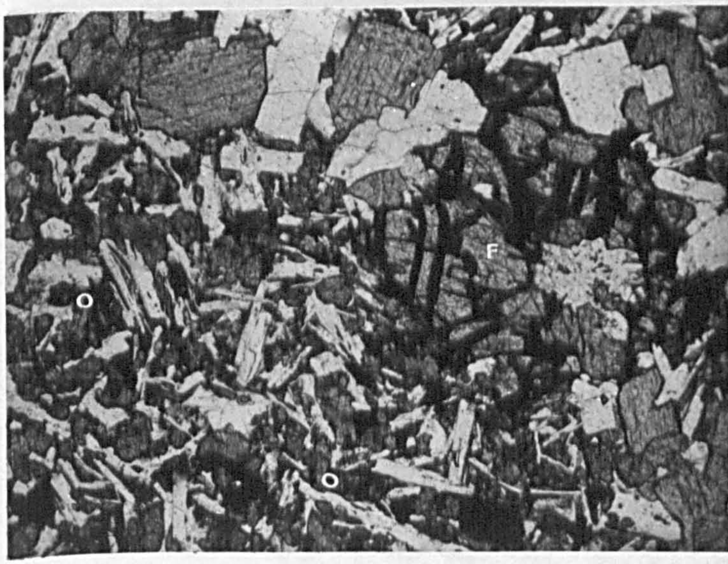
The groundmass in most Type 1 sheets examined was found to consist of an intersertal fabric of small plagioclase laths, with a few small olivine grains, interstitial clinopyroxene and ore, and a glassy or microcrystalline acid residuum (see Figs. 79a, 79b). Some variation in the grain size of the groundmass was found between different sheets and the dolerite of individual sheets was seen to decrease in grain size towards the contacts.

The plagioclase crystals of the groundmass range in size from small euhedral tablets about 1 mm. in length down to small laths about 0.1 mm. in length; these crystals were seen to be twinned on the same laws as the phenocryst plagioclases, and were found to be continuously zoned from cores of high-temperature labradorite (An_{58}) to rims of andesine (An_{40} to An_{32}), this range coinciding with that found in the outer parts of the phenocrysts. The smaller groundmass feldspar crystals were found to have the most sodic core compositions, as was found to be the case in the groundmass of the early basic cone-sheets; as in these sheets a number of small plagioclase crystals of size intermediate between the large phenocrysts and the groundmass crystals were found to be present. These microphenocrysts were found to have core compositions in the range An_{78} to An_{58}, and to have high-temperature optics for compositions more sodic than An_{70}; similar optics were found over the same compositional range in the mantles of the large phenocryst plagioclases in these Type 1 rocks.

Scattered crystals of olivine ranging from about 0.02 mm. to about 0.5 mm. in length were found in the groundmass of all the Type 1 sheets examined; these crystals were found to show subhedral to anhedral equant form, but a few were seen to show some elongation parallel to the c-axis. Crystals representative of the whole groundmass size range given were often found to occur within the area of a single thin section, the smallest examples forming small granules enclosed by the groundmass pyroxene grains and the largest examples often showing irregular outlines which were seen to be sub-ophitically intergrown with groundmass plagioclase laths. These larger grains are interpreted as microphenocrysts. Many of the olivine crystals were found to have a narrow rim of pale green fibrous alteration material.

The composition of the groundmass olivines in one of the Type 1 sheets was found to range from Fa_{28} to Fa_{62}, and this very wide range in composition is taken to indicate that these small crystals are strongly zoned due to crystallization from a liquid undergoing strong and rapid fractionation. These sheets were found to bear phenocrysts of olivine (cores about Fa_{20}-Fa_{23}) and a large number of other sheets were also seen to bear olivine as phenocrysts (1-2 mm.) and as groundmass crystals (see Fig. 80); the compositional ranges of the phenocryst rims and the groundmass (or microphenocryst) olivines are believed to overlap, like those of the three plagioclase types.

Fig. 80



A Type 1 late-set cone-sheet from western Ásmundarnúpur, showing a large forsteritic olivine phenocryst (F) set in a groundmass which bears small olivine crystals (O) of more iron-rich composition which are often partly enclosed by augite; the phenocryst margins enclose the tips of groundmass plagioclase laths in sub-ophitic texture.

Plane-polarized light, x 45 (Specimen Vi 341).

The early separation of large numbers of large olivine phenocrysts from the Type 1 basaltic liquid would cause effective enrichment of the remaining liquid in iron, so that the rapidly precipitated groundmass olivine crystals would be richer in iron than the phenocryst cores, and this is shown by the compositional evidence (see p.524). A large number of the small olivine groundmass granules was found to be enclosed by groundmass clinopyroxene, while other larger grains were seen to be sub-ophitically intergrown with the groundmass plagioclase laths; the grains enclosed by pyroxene would have been effectively removed from the liquid, which thus proceeded to precipitate more iron-rich olivine as groundmass grains or as outer zones to the large phenocrysts.

The small olivine crystals were found to be present in the fine-grained margins of sheets and were also seen as small single euhedral crystals in the dark glassy vein material near the basal contacts of some sheets (see Fig. 44); in both environments, small euhedral crystals of plagioclase and pyroxene were also seen. The occurrence of phenocrysts of plagioclase, pyroxene and olivine in the fine-grained parts of the Type 1 material is taken to indicate that the three minerals crystallized simultaneously for a large part of the cooling history of this material; further evidence of this is given by the presence in the groundmasses of pyroxene and olivine grains forming separate sub-ophitic intergrowths with plagioclase laths of the same composition.

The groundmass clinopyroxene in the Type 1 cone-sheets was found to be a pale pink-brown calcic augite of composition $Ca_{39.5}Mg_{37.5-39}Fe_{21.5-23}$ (Nos. 6 and 9, Fig. 90); this mineral forms small anhedral crystals which sometimes show regular sections perpendicular to the c-axis. These pyroxene grains were found to be interstitial to the plagioclase laths and the olivine grains, often partly or wholly enclosing crystals of either mineral; some of the grains in the coarser-grained groundmasses were found to be of near-uniaxial pyroxene of pigeonitic type. No exsolution textures were seen in these very small groundmass pyroxene grains, and a number of grains were seen to be twinned parallel to (100).

Ore occurs in the groundmass as anhedral grains up to about 1 mm. in size moulded on to grains of plagioclase, pyroxene and olivine and is thus taken to be of late crystallization. Some ore grains were found to show elongated sections.

The final gaps in the fabric are infilled by acid material of varying type. In some sheets this material was seen to be of brownish isotropic glassy material of dusty appearance bearing small apatite rods and occasional elongated zircon crystals; this material may be altered to a greenish fibrous material, and is very similar to the final residua seen in the First Phase basic rocks. Other sheets were found to bear final residua of extremely fine-fret graphic quartzo-feldspathic material, and minute elongated sections of tridymite or paramorphs of this mineral were sometimes seen in these patches.

Small patches of carbonate were found in the final mesh gaps of some of the Type 1 cone-sheets.

Other Intrusions of Type 1 Material

The Gálgagil and Ásmundarnúpur plugs and the small sheets on western Raudkollur are of similar material to the Type 1 cone-sheets; only the Gálgagil rock was examined in thin section, and its mode was found to be:

Phenocrysts:	Plagioclase	4.4
Groundmass:	Plagioclase	38.1
	Clinopyroxene	23.8
	Olivine	4.1
	Ore	6.6
	Interstitial glass	23.0

This rock shows exactly similar mineralogy and texture to the coarser Type 1 sheets, the groundmass plagioclases being commonly 1 mm. in length, and zoned from cores of high-temperature labradorite (An_{61}) to rims of andesine (An_{40}). The plagioclase phenocrysts in this rock were found to have cores of bytownite (An_{85} to An_{80}) and these are zoned to rims of high-temperature andesine (An_{40}). Olivine occurs as microphenocrysts up to 1.0 x 0.5 mm. in section which were found to have core compositions in the range Fa_{20} to Fa_{26}; the rims of these olivine crystals were often seen to enclose the tips of groundmass plagioclase laths in sub-ophitic intergrowth, and as in the Type 1 cone-sheets, the smaller olivine grains (about 0.2 mm. in size) were seen to be free of intergrowth with plagioclase and to be enclosed poikilitically by the groundmass clinopyroxene.

The groundmass clinopyroxene in this rock is a pale pink-brown calcic augite of composition $Ca_{38}Mg_{36}Fe_{26}$(No.11, Fig. 90), and is exactly similar in appearance to that of the Type 1 cone-sheets, often enclosing the tips of groundmass plagioclase laths in sub-ophitic intergrowths. This pyroxene typically forms small anhedral grains up to about 0.5 mm. in size; these may be twinned parallel to (100), and may show near-uniaxial rims of pigeonitic pyroxene.

The ore in this rock shows some tendency to skeletal habit and is seen as elongated sections up to 1 mm. in length, or subhedral polygonal sections up to about 0.5 mm. in width; this mineral appears to be of late crystallization, as it is interstitial to the plagioclase, pyroxene and olivine crystals in the rock.

The final gaps in the dolerite mesh were seen to be filled by a pale brown isotropic glassy material which was often found to bear numerous small elongated ore crystals arranged in parallelism. This glassy material was found to have a refractive index n = 1.560 (±0.002), which corresponds to a silica content of about 56 per cent (Huber and Rinehart 1966); its abundance in this rock indicates the rapid cooling of the olivine-tholeiite.

Type 2

Coarse-grained Feldsparphyric Olivine-Eucrite

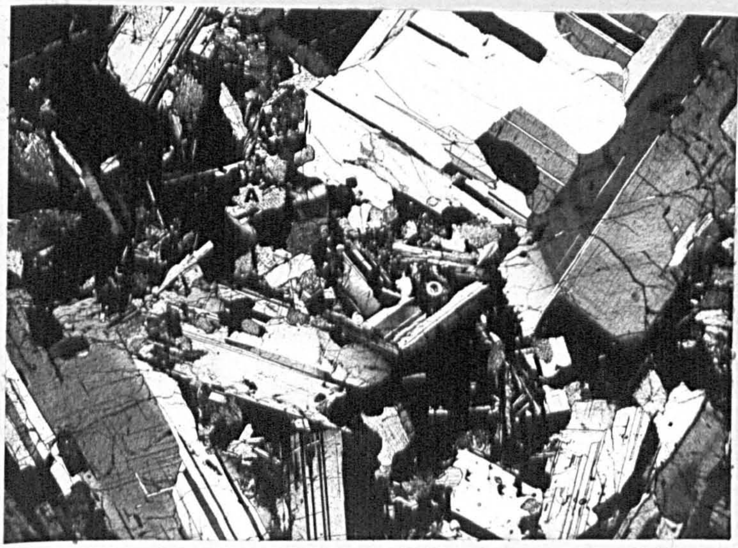
Material of this type was found only in the two cone-sheets lettered "L_E" on Map 2 and in the small intrusion forming the summit of Skessusaeti, and shows the same mineralogy and textures in each intrusion, the small summit intrusion, however, being richer in olivine than the two cone-sheets, bearing 16 per cent of this mineral compared to the 5-6 per cent in the sheets.

The Type 2 material shows similar mineralogy to the Type 1 material, but its grain size is much coarser due to the greater abundance of large plagioclase phenocrysts, which make up over half of the rock (see Fig. 81); the mode of the Type 2 material in the Skessusaeti L_E sheet was found to be:

Plagioclase phenocrysts	56.0
" microphenocrysts	6.7
Olivine phenocrysts	5.5
Clinopyroxene	23.5
Ore	3.0
Interstitial material	5.3

The plagioclase phenocrysts are up to 5 mm. in length, and show tabular form with some flattening parallel to (010). The crystals were found to be twinned on albite, Albite-Carlsbad, Carlsbad and pericline laws, and many were seen to bear small inclusions of ore and ferromagnesian material in the innermost parts of the core. The crystals were found to have broad cores of bytownite in the compositional range An_{90} to An_{80} which commonly make up about 60 per cent of the crystal by volume and may show some discontinuous zoning (see Fig. 81<u>a</u>). The core zones are surrounded by a broad mantle of more sodic plagioclase and a few minor discontinuities may be seen in the zoning at this transition; the greater part of this mantle was found to be of high-temperature labradorite in the range An_{70} to An_{55}, and the outermost zones were found to be of andesine in the range An_{38} to An_{31}. The plagioclase of the mantle was often found to enclose the small groundmass pyroxenes and plagioclase crystals and the small olivine microphenocrysts.

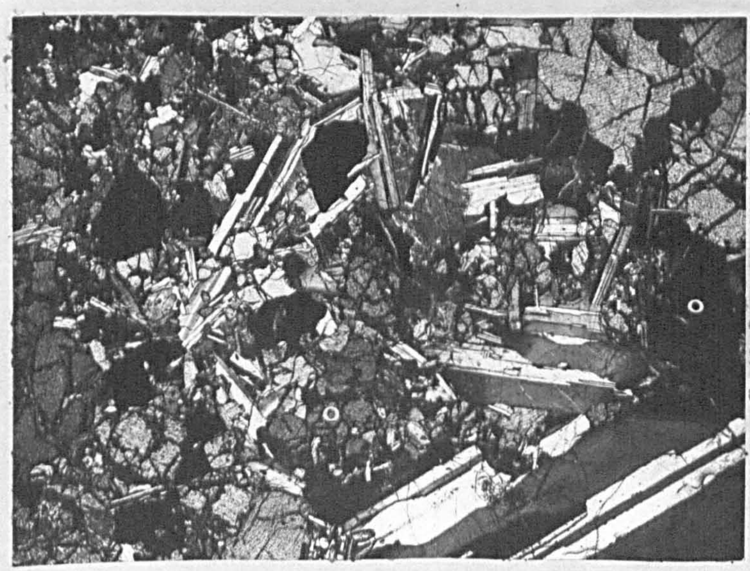
Fig. 81a



Olivine eucrite from the Skessusaeti Type 2 cone-sheet. A large bytownite phenocryst with a clear core mantled by a broad rim of labradorite is seen in the top right corner of the field, and other large plagioclase phenocrysts are also present. The matrix of the rock consists of small grains of augite (A) which may enclose the smaller plagioclase laths and the small microphenocrysts of olivine (O).

Cross-polarized light, x 15 (Specimen Vi 551/b).

Fig. 81b



Olivine eucrite from the small summit intrusion on Skessusaeti (939 m.), showing large zoned bytownite phenocrysts. Anhedral olivine grains (O) are abundant in this rock, and these enclose the tips of groundmass plagioclase laths in the lower part of the field. The rest of the field consists of augite and plagioclase in ophitic to sub-ophitic intergrowth and interstitial opaque ore.

Cross-polarized light, x 15 (Specimen Vi 95).

A number of smaller plagioclase phenocrysts up to about 1.5 mm. in length were found in this rock, and these were found to have core compositions in the region of An_{78}; these crystals are loosely termed microphenocrysts.

Olivine occurs in this rock as small subhedral or anhedral crystals with rounded outlines up to about 1 mm. in greatest length; these crystals were often found to show a length to breadth ratio of 2:1 in the direction of the c-axis, and the larger grains were found to have core compositions in the range Fa_{22} to Fa_{24} (see Fig. 81b). These large olivine grains were sometimes found to be associated in clusters with the large plagioclase phenocrysts. The olivine grains in the Type 2 rock range down to about 0.1 mm. in size and some of the larger ones were seen to enclose the tips of small groundmass plagioclase laths in sub-ophitic intergrowth; no estimate was made of the total range of zoning present in these olivine grains. Many of the grains were found to show rims of greenish or orange-brown fibrous alteration products sometimes associated with opaque ore.

The clinopyroxene in the Type 2 rock is a pale pink-brown calcic augite of composition $Ca_{39.5-41}Mg_{37-40}Fe_{19-23.5}$ (Nos. 2 and 9a, Fig. 90); no isolated phenocrysts of this mineral were found in these rocks and the augite typically forms anhedral grains up to 2 x 2 mm. in area which poikilophitically enclose the small olivine microphenocrysts and the plagioclase microphenocrysts and groundmass crystals. Some grains were seen to show twinning parallel to (100) but no exsolution textures were found in any of the augite grains examined, and narrow zones of near-uniaxial pigeonitic pyroxene were found at the margins of the larger crystals.

Ore forms about 3.0 per cent of the rock by volume, and is interstitial in habit, forming skeletal grains up to 1.5 mm. in greatest length which show elongated or polygonal sections; many of these grains were seen to enclose the tips of the later-formed groundmass plagioclases.

The final gaps in the crystal mesh are infilled by an acid residuum which is similar in appearance to that found in the Type 1 dolerite, and may be of dusty glassy material often showing alteration to finely fibrous green material or pale microcrystalline felsitic material in which small quartz paramorphs after tridymite are present. This residual material may contain small ore granules and small euhedral apatite rods, and its fine grain and its abundance are felt to indicate that the rock cooled quickly.

There is evidence that the Type 2 material in the Skessusaeti L_E sheet encountered First Phase (or similar) material during its ascent to its present position at the centre of the sheet. A small xenolith of material similar in texture and mineralogy to the First Phase H_I rock was found in the eucrite; the margins of this inclusion are indistinct and are felt to be suggestive of incipient remelting and assimilation of its acid interstitial material by the enclosing eucrite.

Type 3

These sheets are fine-grained tholeiites which were seen to differ in several respects to the Type 1 sheets, the most obvious difference being the presence of abundant vesicles in the Type 3 sheets. These Type 3 sheets were also seen to have a much more glassy matrix than the Type 1 sheets, and this is shown in the mode of this rock type. The scattered olivine microphenocrysts in the rock have an elongated habit which contrasts with the equant habit of the olivines in the Type 1 sheets.

The fine-grained tholeiite of the Type 3 sheets is very similar in texture and mineralogy to that of the thin pale grey basalts (tgB) which form the uppermost part of the Vididalur-Vatnsdalur lava pile but is of slightly coarser grain size than the lavas; the mode of a sample from a sheet on the Sandfell ridge was found to be:

Phenocrysts:	Plagioclase	0.1
	Clinopyroxene	0.3
	Olivine	tr
Groundmass:	Plagioclase	16.5
	Clinopyroxene	14.6
	Ore	4.3
	Interstitial glass	35.3
Vesicles		28.9

Small clear plagioclase phenocrysts up to about 4 mm. in length were found in some sheets and these were seen to be tablets about 4.0 x 1.0 x 0.5 mm. in size and flattened in the (010) plane. These phenocrysts were found to be zoned from cores of labradorite (about An_{60}) to rims of andesine (An_{30}); a broad rim of composition An_{50-30} was seen to surround the core in many of these crystals. The zoning in these crystals was sometimes seen to consist of numerous small discontinuities in similar fashion to the zoned cumulus plagioclases in the Hnjúkur core gabbro and the TFB flows (see p.333).

A few small subhedral phenocrysts of pale brown augite occur in some of the Type 3 sheets, and these were found to reach sizes of 0.7 x 0.3 mm.; these crystals occur singly or moulded on to plagioclase phenocrysts, and were not seen to show any exsolution textures.

Scattered fresh subhedral olivine microphenocrysts up to 0.3 mm. in length were found in some of the sheets; these are commonly elongated parallel to the a-axis like the olivines in the thin pale grey basalts (p.19), and were found to have a large optic axial angle which indicates that they are forsteritic types. The length to breadth ratio of these olivines is about 5:1.

No ore phenocrysts were found in these rocks.

The groundmass of the Type 3 sheets is a fine-grained fabric of randomly oriented plagioclase laths up to about 0.5 mm. in length with labradorite-andesine cores (An_{50-40}) zoned continuously to rims of An_{30}. Small equant granules of pale brown augite up to about 0.2 mm. in size are interstitial to or sub-ophitically intergrown with these laths, and these pyroxene grains are also seen to be moulded on to the olivine microphenocrysts; some of these grains have near uniaxial interference figures and they are taken to be pigeonitic types.

Ore occurs in the groundmass as small square or elongated sections up to 0.2 mm. in length which are often seen to be moulded on to the plagioclase and pyroxene grains and are thus taken to be of late precipitation.

The final interstices of the groundmass are occupied by pale honey-coloured isotropic glass which forms about 35 per cent by volume of the rock. The abundance of this glass suggests that the Type 3 sheets solidified very quickly. The glass contains numerous small acicular crystals of opaque ore and clear apatite and is sometimes seen to be cloudy due to the presence in it of minute dust-like particles.

Parts of the glassy material were seen to pass into a pale brown fibrous anisotropic material which shows moderate birefringence; this material was often seen to have a spherulitic structure and to infill or line some of the vesicles in the rock. The fibrous material is very similar in appearance to the fibropalagonite described in the glassy basic rocks of the Hengill area by Saemundsson (1967b, Plate IIc) and is felt to have a similar composition to this material.

Small acicular clinopyroxene crystals similar in form to those found in the Second Phase acid minor intrusions occur in parts of the glassy matrix; these range up to about 0.2 mm. in size, are dotted with minute ore granules, and are associated with very small sodic plagioclase laths. The appearance of these patches is very similar to that of the residual patches described in the thin pale grey basalts (see p.20).

The salient petrographic features of the main types of early and late set cone-sheets are summarized in Table 7.

TABLE 7: COMPARISON OF THE MAIN PETROGRAPHIC FEATURES OF THE VIDIDALUR-VATNSDALUR CONE-SHEETS

Early Set	Late Set
Type 1 Compact tholeiite. Bytownite phenocrysts make up 20-25% by volume of rock. Medium grain size - groundmass pyroxenes up to 0.8 mm. in size. Altered interstitial glass common and locally abundant. Occasional eucrite and gabbro inclusions found.	Type 1 Compact olivine-tholeiite. Bytownite phenocrysts make up to 20% of rock by volume. Medium grain size - groundmass pyroxenes up to 0.5 mm. in size. Fresh interstitial brown glass common and locally abundant. Olivine crystals have near-equant habit.
Type 2 Like Type 1, but bytownite phenocrysts absent or scarce.	Type 2 Compact olivine-eucrite. Coarse grain size - pyroxene crystals up to 1 mm. in size. Small amount of felsitic interstitial material. Olivine crystals have near-equant habit, length to breadth ratio usually less than 2:1.
Type 3 Compact tholeiite. Bytownite phenocrysts make up to 20% of rock by volume. Fine grain size - groundmass pyroxenes up to 0.2 mm. in size. Small amount of altered interstitial glass. Secondary carbonate common throughout.	Type 3 Highly vesicular tholeiite - vesicles make up about 35% of rock by volume. Labradorite phenocrysts make up to 10% of rock by volume. Fine grain size - groundmass pyroxenes up to 0.2 mm. in size. Abundant fresh interstitial brown glass which may be partly altered to fibropalagonite. Olivine crystals commonly of elongated habit, length to breadth ratio about 5:1.
Olivine absent, sheets hydrothermally altered	Olivine present, sheets fresh and unaltered

3-11: THE HJALLIN LENS

This intrusion shows very uniform texture and mineralogy throughout, and is composed of tholeiite almost exactly similar in appearance to that of the basic material in the Gálgagil composite intrusion (see Fig. 84). The mode of a sample from the median level of the body was found to be:

Phenocrysts:	Plagioclase	0.7
	Ore	0.2
Groundmass:	Plagioclase	30.9
	Clinopyroxene	49.7
	Ore	18.0
	Interstitial material	0.5

A few scattered crystals of high-temperature plagioclase with clear cores of labradorite (An_{67}) zoned continuously to rims of andesine (about An_{30}) were found in this rock; these crystals are euhedral numerous minute bleb-like inclusions of the groundmass pyroxene and ore.

Occasional small pale pink-brown augite prisms up to 0.7 x 0.3 mm. in size were found in this rock; these were not seen to contain exsolution lamellae and their rims contain groundmass blebs similar to those seen in the feldspar rims. One greenish rectangular serpentinous pseudomorph 1.5 x 0.5 mm. in size was found, and this may be an original olivine phenocryst.

Small euhedral equant ore phenocrysts up to 0.4 mm. in size occur in the tholeiite and these were sometimes seen to be partly enclosed by the augite phenocrysts, indicating that ore was of relatively early precipitation in this rock.

The groundmass of the rock is an extremely fine-grained intergranular fabric of minute labradorite-andesine laths (cores about An_{50}) up to about 0.1 mm. in length, small stumpy prisms of pale pink-brown augite and small ore cubes. No interstitial material was seen in this fabric, and the three main minerals form a tightly interlocking mesh, which suggests that plagioclase, pyroxene and ore crystallized almost simultaneously from the liquid.

A few small slender rods of apatite up to 0.1 mm. in length are scattered throughout the groundmass.

A small rounded inclusion of dolerite about 5 cm. in diameter was found in one specimen, and this material is of olivine-tholeiite exactly similar in grain size and mineralogy to the Type 1 material of the Gálgagil basic plug (see p.423); this olivine-tholeiite inclusion is believed to have been solid at the time of its incorporation by the lens tholeiite, as it has truncated crystal margins at its edges and bears brown isotropic interstitial glass like that present in the Gálgagil rock.

3-12: ACID INTRUSIONS

1. The Gálgagil Composite Intrusion

(a) The Basic Margins

These parts of the intrusion were found to be of fine-grained tholeiite similar to that of the Type 1 cone-sheets, but no olivine was found in this rock, which consists of a fine-grained mesh of randomly-oriented plagioclase laths up to about 0.5 mm. in length which show lamellar twinning and are zoned from cores of high-temperature labradorite (An_{56}) to rims of andesine (An_{36}). Small grains of pale pink-brown clinopyroxene are interstitial to these feldspar laths, and small ore grains are moulded on to the crystals of these two minerals, the final gaps in the mesh being infilled by a very pale brown isotropic glassy material. The mode of this material is:

Phenocrysts:	Plagioclase	0.6
Xenocrysts:	Plagioclase	0.3
Groundmass:	Plagioclase	46.4
	Clinopyroxene	39.0
	Ore	13.1
	Interstitial material	0.6

Occasional large subhedral grains of plagioclase and pink-brown augite were seen to be set in this fine-grained groundmass, and these show ragged often embayed outlines and irregularly perforated cores filled with brown glass which are taken to indicate that the crystals have been partly resorbed; the plagioclase grains show a very simple twinning pattern, with rarely more than two twin individuals, and are similar in appearance to the plagioclase phenocrysts in the central acid component of the intrusion. One of these plagioclase crystals was found to be of andesine (about An_{31}) and the evidence of disequilibrium shown by this crystal is taken to indicate that it is a xenocryst derived from the central porphyritic acid component of the intrusion; similar xenocrysts of acid plagioclase have been found in the basic parts of other basic-acid composite dykes and lava-flows with porphyritic acid components from eastern Iceland by Gibson and Walker (1963). These authors point out the similarity of the composite bodies in eastern Iceland to the examples cited by Bailey and McCallien (1956) and state that the presence in the basic components of feldspar phenocrysts characteristic of the rhyolitic component of the composite bodies "is generally taken to show that the basalt absorbed some acid magma, probably at an early stage, before extrusion. The xenocrysts are relics of this absorbed material" (Gibson and Walker, op. cit., pp. 315-316). This occurrence of acid plagioclase xenocrysts in the upper basic component of the Gálgagil composite body indicates that this basic material did encounter acid material prior to emplacement, and is taken to indicate that the central acid component of the body and the upper basic component were simultaneously mobile, although at a level below that of the exposed part of the intrusion.

(b) <u>The Central Acid Component</u>

This acid material is a fine-grained dacitic rock bearing scattered phenocrysts of plagioclase, clinopyroxene and ore in a hyalopilitic matrix (see Fig. 82), and its mode was found to be:

Phenocrysts:	Plagioclase	2.9
	Clinopyroxene	0.4
	Ore	0.4
Groundmass:	Plagioclase	42.0
	Clinopyroxene	8.7
	Ore	1.5
	Glass	44.1

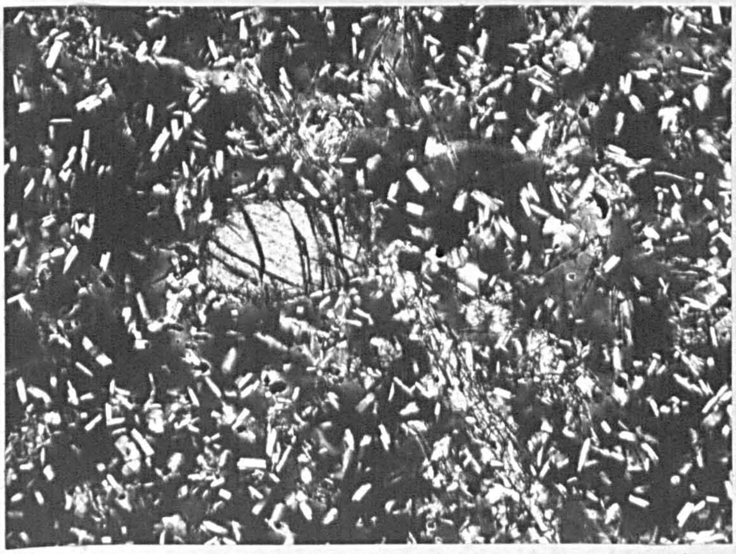
The plagioclase phenocrysts show euhedral lath and tabular sections with respective maximum dimensions of 1.5 and 0.7 mm., and were found to be twinned on albite, Albite-Carlsbad, Carlsbad, and Albite-Ala laws, with occasional pericline twins. These crystals show normal zoning from cores of high-temperature andesine (An_{34}) to more sodic rims (about An_7); the plagioclase phenocrysts occur singly or in clusters with the clinopyroxene and ore crystals and were sometimes seen to enclose these phenocrysts.

One large crystal of high-temperature labradorite (An_{69}) was found in this acid material and shows similarity to the scattered labradorite phenocrysts present in the basic margins of the Gàlgagil intrusion; this crystal is interpreted as a xenocryst acquired from the basic material during mixing prior to emplacement. Similar labradorite xenocrysts in the acid parts of composite sheets have been reported from eastern Iceland (Gibson and Walker 1963) and Snaefellsnes, western Iceland (Sigurdsson 1966a, p. 85).

The clinopyroxene in this rock is a pale green faintly pleochroic type which forms subhedral prismatic phenocrysts of rounded outline up to about 1.0 x 0.4 x 0.4 mm. in size; these crystals are sometimes twinned parallel to (100) and are often moulded on to plagioclase phenocrysts. The composition of the pyroxene was found to be $Ca_{48}Mg_{22.5}Fe_{33.5}$ (Hess, 1949, and Muir, 1951, in Deer, Howie and Zussman 1965, Vol. 2, Fig. 41), or $Ca_{48}Mg_{24}Fe_{28}$ (Carmichael 1960b, Fig. 3). Both these compositions are much more calcic than the examples of clinopyroxene phenocrysts from the Thingmúli acid rocks described by Carmichael (1967a) and fall into the hedenbergite field (see Fig. 90, No. 12). No evidence of exsolution was found in these hedenbergitic phenocrysts, but many crystals were found to show a narrow rim with "spongy" texture (see Fig. 82); a similar spongy appearance has been found in ferroaugites from Skruthur, eastern Iceland, by Carmichael (1960b), who has described the phenomenon as "suggestive of incipient recrystallization" (op. cit., p. 311); the Gálgagil rims are felt to indicate reaction between the pyroxene and its enclosing liquid.

The pyroxene phenocrysts in the Gálgagil rock were sometimes seen to enclose the small ore phenocrysts also present; a similar relationship between augite and ore phenocrysts in acid glasses has been described in examples from eastern Iceland by Carmichael (1963a)

Fig. 82



The dacitic rock of the central acid component of the Gálgagil composite sheet. A clinopyroxene phenocryst can be seen in the centre of the field, and the margins of this crystal are rounded and show a narrow rim with "spongy texture". The surrounding groundmass is composed of small andesine laths, small acicular clinopyroxene crystals and occasional small dark equant ore grains set in a glassy matrix of dusty appearance. No plagioclase phenocrysts are seen in this part of the field.

Plane-polarized light, x 45 (Specimen A 15a).

and is taken to indicate the early crystallization of ore in these rocks. The ore phenocrysts on the Gálgagil rock were commonly found to have small subhedral square sections with rounded corners, and to range up to about 0.2 mm. in size.

No olivine was found in this rock either as phenocrysts or groundmass crystals.

Small plagioclase laths of length 0.1 to 0.2 mm. make up about 40 per cent of the groundmass of the rock; these crystals show a limited development of lamellar twinning, and some were seen to show part development of skeletal habit, having imperfect forked "swallow-tail" terminations which are felt to indicate rapid crystallization.

These groundmass feldspar laths were found to be zoned from cores of high-temperature andesine (about An_{25}) to margins of more sodic feldspar (An_7).

Small pale green clinopyroxene grains were found to form nearly 9 per cent of the groundmass of the rock; these crystals appear to have predominantly stumpy anhedral forms up to about 0.2 mm. in length in the upper part of the acid component of the sheet, and predominantly acicular subhedral forms up to 0.4 mm. in length in the inner part of the sheet. These crystals were too small for accurate optical measurements to be made, but are similar in general characteristics to the larger phenocrysts and are possibly of more iron-rich composition than these types; the small crystals were, however, not found to show spongy rims or any other indications of disequilibrium of the type seen in the large phenocrysts. A large number of the small clinopyroxene phenocrysts were seen to be partly moulded on to the groundmass plagioclase laths, and this is taken to indicate that their period of crystallization partly coincided with and partly succeeded that of plagioclase in this rock.

Ore is seen in the groundmass as small euhedral square sections commonly 0.02 mm. in size, and these grains were sometimes seen to be partly enclosed by the groundmass pyroxene grains.

The matrix of the rock is a pale brown glass of dusty appearance due to the presence in it of numerous minute particles and contains scattered minute rods of apatite; the refractive index of this glass was determined as n = 1.481 (± 0.002) which indicates that it has a silica content of about 76.5 per cent (Huber and Rinehart 1966).

The textural relationships described above appear to show great uniformity throughout the acid component of the Gâlgagil sheet except in the "mottled zone" (p.273). In this zone, the hyalopilitic groundmass of the acid rock was seen to be spotted with small rounded areas showing similar mineralogy but different texture to the surrounding material. The patches found ranged up to about 12 mm. in greatest length and appear to be mostly of globular form; no implication as to the mode of formation of the patches is implied by the use of the adjective "globular". The patches were found to be of two types.

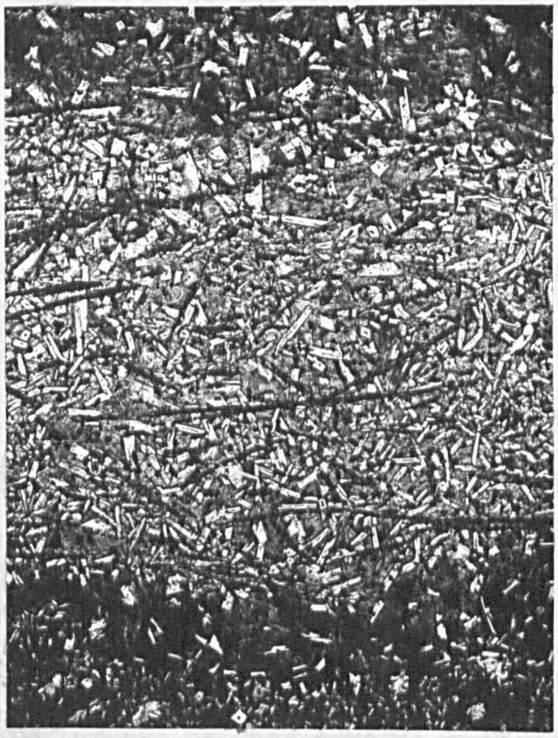
Type 1: These patches were found to be apparently continuous with the rest of the glassy matrix of the acid rock, but of a darker brown glass of more dusty appearance than that of the main part of the groundmass; the patches were also seen to be richer in small plagioclase laths than the surrounding groundmass, the laths in each environment being apparently exactly similar. These patches were found to range up to 5 mm. in diameter.

Type 2: These patches show a far more striking difference in texture to the surrounding groundmass, being of coarser crystallization than this material, and their matrix is composed of light yellow-brown glass which contrasts with the darker brown colour of the surrounding material but appears to be continuous with it (see Fig. 83a); the lighter colour of the patch material is seen in thin section to be largely due to the almost entire absence of dust-like particles.

The Type 2 patches were found to range up to about 12 mm. in greatest length and most were found to show ovoid sections, but a few were seen to show streaky lenticular form. The most remarkable feature of these Type 2 patches is the presence in them of numerous highly elongated acicular pale green clinopyroxene crystals; these crystals may reach lengths of 3 mm. but are commonly 2 mm. in length along the c-axis with a length to breadth ratio of 50:1 (see Fig. 83). The margins of the crystals enclose large numbers of minute opaque ore granules, and few ore grains were found away from the pyroxene crystals in these patches.

The pyroxene needles were sometimes seen to be partly moulded into the acute angles between adjacent plagioclase crystals in the patches and this is taken to indicate that the pyroxene crystallized shortly after the plagioclase crystals in the same sequence as that indicated by the textures in the other parts of the groundmass of the acid rock. The plagioclase crystals in the Type 2 patches are small euhedral columnar crystals commonly 0.4 x 0.05 x 0.05 mm. in size (i.e. about twice the size of the plagioclase crystals in the surrounding ground-mass material); these patch plagioclases were often seen to be hollow, with a void core elongated parallel to the c-axis and filled by the glassy matrix material (see Fig. 83b). The composition of the largest plagioclase crystals from both one of these patches and the surrounding groundmass was compared, determinations being made using

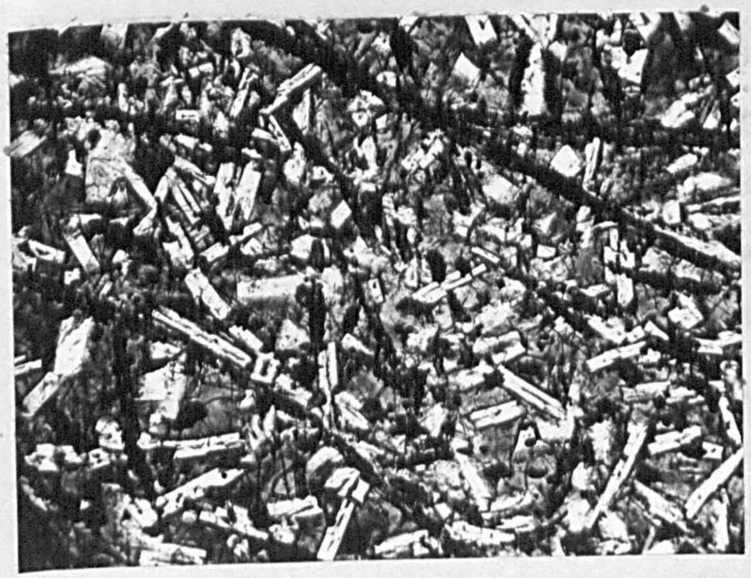
Fig. 83a



A Type 2 patch from the mottled zone of the acid component of the Gâlgagil composite sheet, showing the marked colour contrast between the matrix material in the patch and surrounding groundmass. The extremely elongated acicular habit of the dark clinopyroxene crystals is readily seen. The hollow columnar plagioclase crystals in the patch are of larger size than those in the surrounding groundmass.

Plane-polarized light, x 15 (Specimen Vi 172).

Fig. 83b



Detail of Fig. 83a, showing more clearly the acicular clinopyroxene crystals and the high concentration of minute ore granules along these crystals. The skeletal habit of the plagioclases is also noticeable, several rectangular annular sections with central infillings of glassy matrix material being seen. A few small crystallites can be seen in the interstitial glassy matrix.

Plane-polarized light, x 45 (Specimen Vi 172).

the Rittmann method on four crystals from each environment; the composition of the cores of the feldspar crystals was found to lie in the compositional range An_{30} to An_{34} in both groups. The skeletal habit of these crystals is taken to be the result of rapid growth, by analogy with the similar form of the rapidly-precipitated plagioclase crystals in the craignurites of Mull (Bailey et al. 1924, p. 225, Fig. 33A).

The margins of the patches were not found to show any sharp discontinuity against the surrounding groundmass material, but in some of the patches the pyroxene and plagioclase crystals were seen to be arranged in open spherulitic aggregates; in the smaller patches these spherulites were seen to radiate from the centre of the patch and in the largest patches several such contiguous spherulites were found.

A number of very small clinopyroxene crystallites up to about 0.1 mm. in length were commonly found in the glassy matrix of the Type 2 patches, as well as a few euhedral apatite needles (see Fig. 83b). Some of the patches were also found to contain occasional phenocrysts of andesine and pale green augite similar in size and appearance to those seen in the surrounding material.

The mode of formation of these patches is not fully understood, but the equivalence of the most calcic groundmass plagioclase compositions both inside and outside the patches is taken to indicate that the patches assumed their individuality at a time not much later than the precipitation of the most calcic groundmass plagioclases; the abundance of hollow-cored plagioclase within the patches and the apparent scarcity of such crystals outside the patches is felt to suggest that the plagioclase crystallized under different physical conditions in each of the two environments. The similar compositions of the plagioclase types are taken to indicate that they crystallized simultaneously.

No compositional data are available for the clinopyroxene crystals in each of the two environments, as the determination of optic axial angles and refractive indices is difficult due to the small size of the crystals. Some chemical difference between the two environments may be indicated by the markedly higher concentration of ore grains within the groundmass compared to the surrounding material.

One further textural feature of the Gálgagil acid material indicates that separate crystallization of the more calcic hollow patch plagioclases and the groundmass plagioclases began before emplacement of the acid material at the present level. These crystals are set in a glassy matrix, and it seems unlikely they would attain lengths of 0.4-1.0 mm. on the almost instantaneous chilling evidenced by the texture of the matrix; in addition, the outermost zones of these feldspar crystals have a composition of An_7, and this presumably represents the feldspar phase in equilibrium with the liquid at the instant of chilling. The balance of this evidence is felt to indicate that the groundmass andesine-oligoclases are more accurately interpreted as microphenocrysts which were suspended in the acid liquid at the time of intrusion.

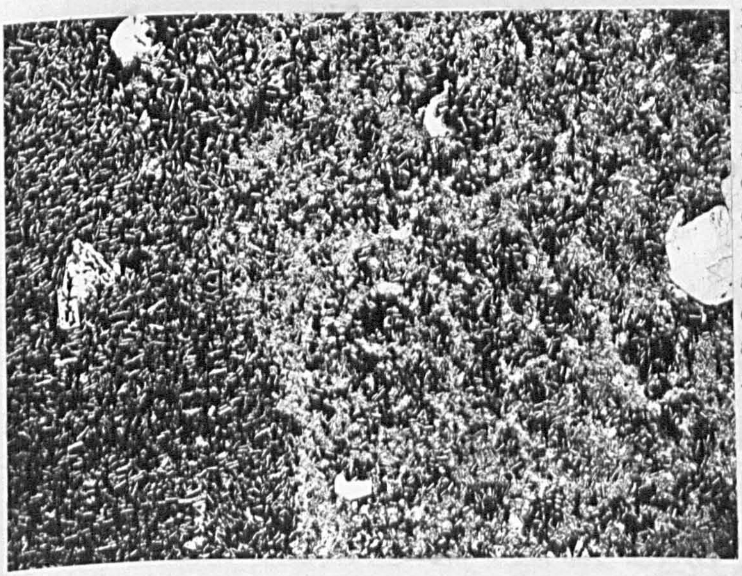
(c) The Composite Zone

The abundant rounded bodies of basic material found in the composite zone of the Gâlgagil composite sheet (p. 274) were found to be of olivine-free fine-grained dolerite exactly similar to the material seen in the marginal dolerite components of the sheet; these bodies are formed of an intersertal mesh of randomly oriented plagioclase laths up to about 0.5 mm. in length with cores of labradorite (An_{56}) zoned to andesine (An_{36}). A few laths were found to show parallelism with the contacts of the bodies (see Fig. 85b).

The pyroxene in the basic material is a pale pink-brown augite which forms small granules interstitial to the plagioclase laths, and small opaque ore grains are moulded on to the plagioclase and pyroxene.

Occasional corroded crystals of andesine were found in this basic material and these often have irregularly perforated interiors, although the margins of the crystals are often entire (see Fig. 84); the perforations in these feldspar crystals are indicative of corrosion and bear brown glassy material and the crystals are interpreted as xenocrysts which originally formed part of the phenocryst assemblage of the acid component of the Gâlgagil intrusion. The form of the crystals is exactly similar to that of the xenocrysts found in the basic margins of the intrusion, and also to examples from a Skye composite sheet figured by Harker (1904, Fig. 47F, p. 220). A few subhedral clinopyroxene phenocrysts up to about 0.7 mm. in size were also seen in the basic bodies and these were rarely found to show perforations, but were often seen to be of pale green faintly pleochroic material similar to the pyroxene phenocrysts in the acid component; many of the crystals examined showed a narrow rim of pale brown clinopyroxene and were seen to have rounded but not embayed margins. These pyroxene crystals are believed to be xenocrysts derived from the acid component of the intrusions and the brown rims may be "reversed zones" of more magnesian augite formed as the result of reaction between iron-rich pyroxene and more magnesian liquid.

Fig. 84



Detail of an acid component-basic inclusion interface showing the contrasting textures of the dark basic material (left of interface) and the light acid material (right of interface). A small cluster of corroded andesine xenocrysts can be seen in the basic material, and an uncorroded andesine phenocryst can be seen in the acid material at the right-hand border of the field.

Plane-polarized light, x 15 (Specimen C 1).

The presence of these xenocrysts of plagioclase and pyroxene in the basic bodies is felt to be further evidence of some mechanical mixing of the basic and acid material prior to emplacement of the separate components of the intrusion.

The only striking difference in texture between the dolerite of the basic bodies and margins is the greater abundance in the bodies of pale honey-brown glass similar in type to that forming the matrix of the acid centre of the intrusion; this material may be seen in small patches throughout the rock which appear too large to be interpreted as final acid residua of normal tholeiite crystallization, and its presence in the basic rock is believed to show that the dolerite was in the form of dense but incompletely consolidated loose crystal aggregate suspended in the acid glass.

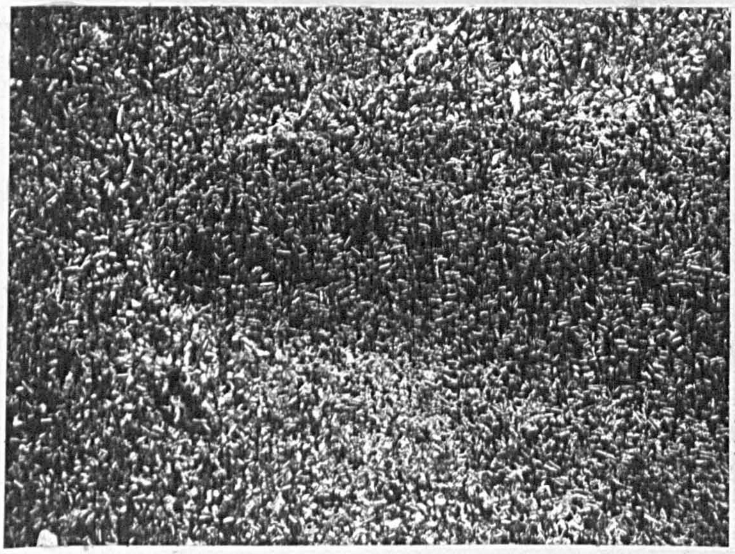
As has already been mentioned, the dolerite of the basic bodies shows similar grain size to that of the basic margins of the intrusion and no decrease in grain size was found towards the margins of any of the basic bodies (see Figs. 85a and 85b). Fine-grained margins have been found at the margins of basic bodies enclosed in acid material in composite lava flows and intrusions from eastern Iceland by Gibson and Walker (1963) and in similar intrusions in St. Kilda by Wager and Bailey (1953), and have been convincingly shown to be the result of basic magma chilling against cooler acid magma. The absence of such fine-grained margins to the Gâlgagil basic bodies is taken to represent total lack of such strong chilling.

No evidence of chilling was found in the acid material at the basic-acid interfaces in the Gâlgagil bodies but this would be difficult to detect in a glassy rock.

The form of the basic bodies indicates that they were entrained as plastic material (see p.275), and further evidence of this is seen in thin section; the margins of some of the bodies are seen to be slightly diffuse due to the inter-crystal gaps being wider at the periphery than at the centres of the bodies. This is felt to suggest that the component crystals of these bodies were loosely packed at the peripheries, and the structure of the bodies in these cases is analogous to that of a large loose pile of match-sticks. This loose zone in the body margins is seen to be invaded by the glassy matrix of the acid material, but no obvious mineralogical differences or hybridization effects comparable to those seen in the diffuse zones between the Urdarfell diorite and H_G rock were found in the Gâlgagil rocks; this is felt to be due to the rapid final cooling of the acid material, and the basic and acid material on either side of the interfaces can be seen to preserve their distinctive mineralogy and texture (see Fig. 85a and 85b).

To sum up, the available evidence is taken to indicate that the composite zone was formed by the edge of a moving mass of viscous acid material scouring the inner loosely consolidated surface of a newly emplaced basic lining to the fissure now occupied by the intrusion. This scouring caused parts of the more or less plastic basic material to be plucked away from the basic lining, and these inclusions (previously referred to as "bodies") were then carried along in the lower part of the acid material; some rolling and rounding of the basic inclusions resulted during transport from the site of incorporation to their present position.

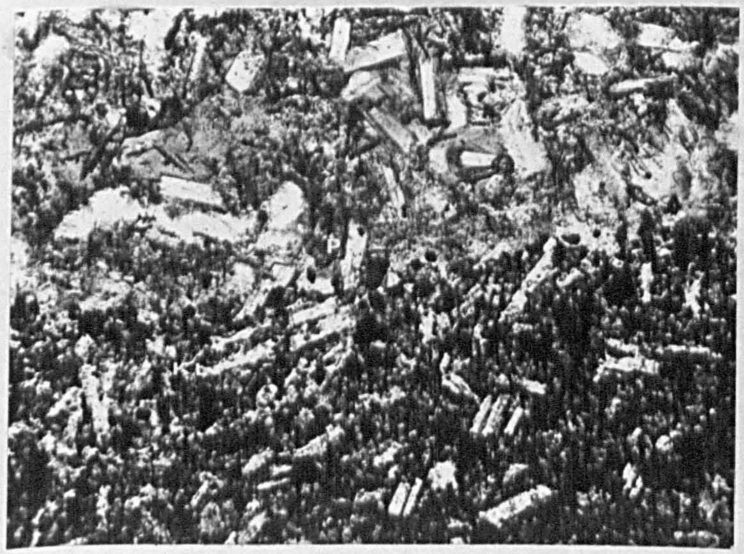
Fig. 85a



The composite zone of the Gálgagil intrusion. A dark elongated inclusion of fine-grained dolerite with numerous small plagioclase laths and uniform grain size throughout occupies the median level of the field; one end of this inclusion can be seen towards the left edge of the field, and the inclusion becomes diffuse towards the lower right corner of the field. The acid host material has a lighter colour than the basic material. The pale streaks near the closed end of the inclusion are small cracks filled with carbonate.

Plane-polarized light, x 15 (Specimen C 3).

Fig. 85b



Detail of the closed end of the basic inclusion figured in Fig. 85a showing the uniform grain size of the basic material at the interface, and the lack of obvious mechanical mixing of the light-coloured acid material and the dark basic material. The plagioclase crystals in the basic rock show some parallelism with the interface, and one small labradorite lath (P) of the basic rock can be seen to protrude into the acid material.

Plane-polarized light, x 100 (Specimen C 3).

2. The Krossdalur Intrusion

The rock forming this intrusion is holocrystalline throughout, and shows mineralogical and textural similarities to the 50-degree sheet south of Raudkollur and the acid component of the Gálgagil intrusion. No olivine was found in this Krossdalur rock, but phenocrysts of plagioclase, clinopyroxene and ore are present. The mode of the rock was found to be:

Phenocrysts:	Plagioclase	2.0
	Clinopyroxene	0.7
	Ore	0.1
Holocrystalline matrix		97.2

The plagioclase phenocrysts are clear, and range up to about 2 mm. in length, commonly showing euhedral lath and tabular sections which may have slightly rounded corners; these crystals were found to be twinned on albite, Albite-Carlsbad and Carlsbad laws. The cores of the crystals are of high-temperature andesine (An_{41}) and the range of zoning in these crystals appears to be small; zoning is only noticeable at the very margin of the crystals which have a composition of about An_{20}. Some of the more calcic plagioclase phenocrysts were seen to have slightly embayed rounded margins indicative of magmatic corrosion and small perforations in the cores of these crystals were seen to be filled by glassy material bearing minute clinopyroxene needles. The appearance of these glassy patches is similar to that of the groundmass in the Gálgagil dacite.

Phenocrysts of pale green faintly pleochroic clinopyroxene were also found in the rock and these show subhedral prismatic forms up to about 1.0 x 0.4 mm. in size with occasional twinning parallel to (100); these pyroxene crystals are so similar to the ferroaugite-hedenbergite types found in other acid minor intrusions in the area that they are taken to be of similar composition. A number of these crystals were found to show spongy rims similar in appearance to those observed in the pyroxene phenocrysts of the Gálgagil intrusion (p.438), and one crystal in the interior of the intrusion was seen to have strongly embayed margins in which a narrow rim zone rich in minute ore granules had developed; the development of these rims is felt to indicate that the pyroxene phenocrysts were not in equilibrium with their environment. No striations suggestive of exsolution textures were found in these pyroxenes, and the crystals were often seen to enclose small ore phenocrysts and to be moulded on to the plagioclase phenocrysts, indicating that pyroxene was the last phenocryst phase to be precipitated from the liquid.

A few small opaque ore phenocrysts showing euhedral to subhedral equant form were found in the rock and these were often seen to be enclosed by the plagioclase and pyroxene phenocrysts, indicating that ore was the first mineral to crystallize from the liquid.

The groundmass of the rock is a fine-grained holocrystalline fabric which shows some decrease in grain size towards the contact. The finest-grained marginal part of the intrusion has a groundmass of ragged interlocking feldspar grains dotted with small opaque ore granules; small subhedral acicular crystals of pale green clinopyroxene similar in appearance to that of the phenocryst phase are scattered throughout this fabric and show random orientation. No gaps were found in this fabric, except for a few small voids filled with clear anhedral quartz grains, and no final glassy residuum of the type found in the 50-degree sheet was found in this rock.

The marginal facies of the rock grades into the main facies by increase in the size of the feldspar and clinopyroxene crystals of the groundmass. The feldspars in the main facies are euhedral laths up to about 0.2 mm. in length which show simple lamellar twinning, there being rarely more than two twin individuals in any crystal. The cores of these crystals were found to be of oligoclase (about An_{20}) and these are zoned continuously towards the margins; the outermost zones of some crystals were seen to show extremely narrow shadowy twin lamellae parallel to (010). The outermost zones of the groundmass feldspar laths pass with apparent continuity into the feldspathic component of extremely fine-fret micrographic intergrowths, in similar fashion to the groundmass feldspars in the 50-degree sheet and the Kornsá sheet.

The small acicular groundmass clinopyroxenes in the main facies of the Krossdalur intrusion are longer than those seen in the marginal facies, and range up to 0.7 mm. in length with a length to breadth ratio of 15-20:1. The margins of the pyroxene crystals can be seen to enclose small ore granules, and other small ore granules are scattered throughout the groundmass.

The final gaps in the mesh are filled by extremely fine-fret micrographic quartz-feldspar intergrowths which were often found to form complete mantles to the small groundmass oligoclase laths; some of these intergrowth areas were seen to pass continuously into small areas of clear quartz which may themselves enclose very small euhedral twinned feldspar laths.

Small euhedral rods of apatite and colourless zircon were also found scattered throughout the groundmass.

CHAPTER 4

MINERALOGY OF THE VIDIDALUR-VATNSDALUR INTRUSIVE ROCKS

4-1 DETERMINATIVE METHODS

1. FELDSPARS

(a) PLAGIOCLASE FELDSPAR

The compositions of 295 plagioclase crystals from 68 rocks were determined on a Leitz 5-axis universal stage, using the Köhler-Reinhard methods; stereographic plots of the pole of the composition plane and the three optical directions were made for each individual of selected twin pairs in each crystal. This procedure was carried out 2 to 5 times for each crystal until a triangle of error of side less than 2 degrees of arc was obtained; the Köhler angles $\alpha\alpha'$, $\beta\beta'$, $\gamma\gamma'$ were measured in the manner described by Reynolds (1951, p. 234) and were then compared with the revised determinative curves of Burri, Parker and Wenk (1967) to obtain the anorthite content and structural state of the plagioclase. These curves were used in preference to those drawn from the results of van der Kaaden (1951), as they embody more data in the range An_0 to An_{30} than was previously available.

The main purpose of determining the structural state of the plagioclases was to ensure that their composition was determined from the correct curve; this is not possible when using the Rittmann zone method (maximum extinction angle on (010)) and indiscriminate use of this method may result in errors of the order of 10% An, which may be critical in the study of plagioclases from intermediate rocks.

The compositions obtained by the Köhler-Reinhard methods are set out in Table 9 and Part 1 of the Appendix under the heading " U - stage "; the accuracy of the determinations is estimated to be ± 2% An.

In the case of the plagioclase phenocrysts of the coarse-grained acid rocks, the twin axes for each stereographic plot were transposed by rotation of β to the origin of the stereogram. The average of the two twin axis positions obtained for each crystal was then compared with the twin-axis migration curves of Burri, Parker and Wenk (1967); the co-ordinates of these transposed twin axes are given in Table 9 with $+\gamma$ at $\lambda = 0^\circ$ and $\phi = +90^\circ$ and β (the centre of the stereogram) at $\lambda = 0^\circ$ and $\phi = 0^\circ$, and the plots are shown in Fig. 88.

The Rittmann zone method was used to determine the compositions of the marginal zones of plagioclase crystals once their structural state was known.

The optic axial angle $2V_\alpha$ of the more sodic plagioclases was determined orthoscopically in ordinary light for those crystals in which both optic axes were directly observable, six determinations being made in the 45-degree position and six in the 135-degree position. The average of these twelve readings was taken as the final value of $2V_\alpha$ and these results are shown in Table 8; the accuracy of these determinations is estimated to be $\pm 2^\circ$.

The total range of zoning of the plagioclase in selected rocks was determined by measurement of the maximum and minimum refractive indices (γ' and α') on cleavage fragments by the immersion method; the final adjustments to the liquids were made in monochromatic sodium light and their refractive indices were measured on an Abbé refractometer, care being taken to keep both microscope stage and refractometer prism at the same temperature. The n_β refractive index was determined similarly for selected crystals picked from thin sections and the accuracy of all the refractive index determinations is estimated to be $\pm$ 0.002. The values obtained were compared with the curves of Chayes (1952), Smith (1958), and Burri, Parker and Wenk (1967) and the plagioclase compositions obtained by this method show satisfactory agreement with the universal stage values; the refractive index determinations and other optical data are given in Part 1 of the Appendix.

(b) ALKALI FELDSPAR

The optical axial angle $2V_\alpha$ was determined for a number of alkali feldspars from acid rocks, using the same methods as for the plagioclase feldspars (see p.454); this data is given in the following text and in Table 10.

A number of thin sections of acid rocks were etched with hydrofluoric acid and stained with sodium cobaltinitrite solution to test for the presence of alkali feldspar; the procedure used was that of Keith (1939).

2. P Y R O X E N E S

The compositions of 16 calcium-rich clinopyroxenes from the Vididalur-Vatnsdalur intrusive rocks were determined using values of $2V_\gamma$ and β refractive index as these are the significant diagnostic optical properties (Brown, 1957).

The apparent optical axial angle $2H_\gamma$ was measured orthoscopically on the universal stage for those grains in which both axes were directly observable, six rotations being made in the 45-degree position and six in the 135-degree position. The final settings were made in monochromatic sodium light; the accuracy of these measurements is estimated to be $\pm 1^\circ$. Five to six crystals were measured in this way in most of the rocks studied and the ranges and average values of $2H_\gamma$ are given in Table 11; the variation of these $2H_\gamma$ values may be due to zoning of the pyroxene in the manner described for the Thingmúli pyroxenes by Carmichael (1967a).

The β refractive index was measured by immersion methods for five to six (100) parting tablets from crushes of each rock using the method outlined by Deer, Howie and Zussman (1965, Vol. 2) or on oriented grains picked from thin sections; the final adjustments to the liquids were made in monochromatic sodium light and their refractive indices were determined on an Abbé refractometer. These determinations are estimated to have an accuracy of ± 0.002.

The β refractive index values were used to calculate values of $2V_\gamma$ from the relation :

$$\sin V = \frac{\sin H \cdot n}{\beta}$$

where n is the refractive index of the universal stage hemispheres.

these values are given in Table 11.

The compositions of the clinopyroxenes were determined from the curves of Hess (1949) and Muir (1951), to maintain consistency in what is a broad range of clinopyroxene compositions; these curves do not, however take into account the possible effects of exsolution in the pyroxenes, and their limitations have been discussed by Brown (op. cit.) and Carmichael (1960b). The compositions determined are plotted in Fig. 90.

The compositions of the three iron-rich pyroxenes from acid rocks were also determined from the revised curve of Carmichael (1960b), from which they are more calcium-rich than the compositions obtained using the Hess-Muir curve; these values are not plotted in Fig. 90, but are given in Table 11.

As the range in $2V_\gamma$ values for the determined pyroxene appears to indicate some zoning, the compositions obtained are taken to represent the bulk compositions of the individual pyroxenes.

The optic axial angle $2V_\alpha$ and the refractive index β were determined for the sodic pyroxene in the MU granophyre and the orthopyroxene in the Breidabólsstadur pitchstone using the same methods as for the calcic clinopyroxenes. The compositions of these minerals were estimated from the curves of Deer, Howie and Zussman (1965, Vol. 2, Figs. 10 and 28).

3. O L I V I N E

The compositions of the olivines from five rocks were derived from determinations of the β refractive index on the cores of oriented grains picked from thin sections, as the irregular cleavage fragments formed by crushed olivines do not allow ready location of the main optical directions. The β refractive index was determined by immersion methods and the final adjustments to the liquids were made in monochromatic sodium light; the refractive indices of the liquids were then measured using an Abbé refractometer, a Leitz-Jelley refractometer being used for liquids of refractive index greater than 1.800. The values obtained are estimated to have a accuracy of $\pm$ 0.002 (below 1.800) and $\pm$ 0.005 (above 1.800).

The compositions were derived by comparison of the refractive index values with the curves of Deer, Howie and Zussman (1965, Vol. 1, Fig. 11.); iron-rich olivine was determined using the revised curves of Carmichael (1960b). The results are given in Table 14, and the average olivine compositions are plotted on the Mg-Fe baseline of Fig. 90; the numbering of the specimens is the same as that used for the pyroxenes in Table 11, and pyroxenes and olivines from the same specimen are joined by tie-lines in Fig. 90.

Direct measurements of the optical axial angle $2V_\alpha$ were made for the iron-rich olivines by the same methods as those used for $2V_\gamma$ of the pyroxenes and the results were compared with the curve of Carmichael (1960b). The accuracy of the $2V_\alpha$ determinations is estimated as $\pm 2^\circ$.

No optic axial angles were measured for the magnesian olivines as these have 2V near 90°, the measurement of which is subject to considerable error (Johnston, 1953; Wyllie, 1959).

M I N E R A L S

4-2 PLAGIOCLASE FELDSPAR

Structural State of the Plagioclases: General Considerations

The different optical orientations of volcanic and plutonic plagioclases of the same composition were first described by Köhler (1941) who suggested that the difference in optics was the result of high-temperature crystallization in volcanic rocks and low-temperature crystallization in plutonic rocks. The two types of orientation thus became known as high-temperature and low-temperature optics, and were subsequently recognized in the plagioclases of a large number of igneous rock series and correlated with the existence of high and low structural types; a good bibliography of these occurrences and an outline of the history of development of these ideas has been given by Reynolds (1951).

Data for the discrimination of high- and low-temperature optics in plagioclases was produced by van der Kaaden (1951) and this has recently been added to by Burri, Parker and Wenk (1967).

In a study of the plagioclases of hypabyssal rocks, Muir (1955) found optical orientations intermediate between the high - and low-temperature types, and he suggested that these represented structural states transitional between the high and low types. The concept of ordering was introduced into the study of plagioclases and this has been discussed by Slemmons (1962), the high temperature plagioclases being disordered plagioclase lattices and the low-temperature types being ordered lattices. The essential differences between the two structural states have been concisely expressed by Gay and Muir (1962, pp. 565-66) in a study of the plagioclases of the Skaergaard intrusion: "For a plagioclase of a particular composition, two limiting structural states (low and high) can be defined. The low state corresponds with the atomic arrangement stable at temperatures low enough to prevent any effective thermal migration of the atoms; the limiting high state is determined by the atomic arrangement stable at temperatures just below the melting point. Between these two limiting states, there can exist a complete and continuous range of transitional structural states, each of which represents an equilibrium atomic arrangement at a particular temperature. It has been clearly established that the nature of the atomic arrangements is such that the transformation between different structural states is not instantaneous; the conditions obtaining during crystallization in natural rock-forming processes may very often not be those of thermodynamic equilibrium, so that the occurrence of metastable states must be expected. Examination by some physical methods, usually optical or X-ray, gives properties which reflect the atomic configuration that exists within the feldspar; we may then assign structural categories, such as high, high-transitional, or low. However, these determinations do not fix the previous thermal history of the specimen with certainty...deductions concerning the thermal history of the rocks in which the plagioclase occurs must necessarily be supported by other evidence, which can often be provided by a study of the associated minerals."

Gay and Muir (op. cit.) suggested as a result of their optical and X-ray work on the Skaergaard plagioclases that the gradual changes in structural state of these feldspars represented an inversion relationship broadly similar to that which produced the changes which have occurred in the pyroxenes of the Skaergaard intrusion (Brown, 1957); they recognize that these processes "are, in the main, sluggish and require time for equilibrium to be obtained. Thus the history of the rate of cooling subsequent to crystallization is a critical factor in determining the final condition of the mineral..... It is probable that...there is a small critical temperature range within which there are rapid changes in the degree of order of the feldspar. Above this range, quenching from a particular temperature or annealing the feldspar at the same temperature will have much the same result. If the plagioclase is cooled slowly through this range, it will invert into a low structural state; if, however, it is not cooled slowly through this range there are an infinity of metastable structural states between low and high into which it may pass." (op. cit. p. 577-78).

These inversion relationships are also controlled to some extent by pressure and concentration of volatile constituents, but Gay and Muir (op. cit.) admit that present data are insufficient to assess the precise function of these factors.

Structural State of the Vididalur-Vatnsdalur Plagioclases.

The structural state of the bytownites in the basic rocks studied is not known, as the optical methods are of no use in distinguishing between the two structural types in plagioclases more calcic than An_{70}; Reynolds (1951) has demonstrated that the Köhler angles for high-temperature plagioclase in the range An_{70-100} lie within the limits of error of measurements on low-temperature plagioclases. In addition, Slemmons (1962) has pointed out that all optical and X-ray methods are relatively ineffective in distinguishing between high and low structural states due to the similarity in structure of the two types of plagioclase.

The Köhler angles of nearly all of the plagioclases more sodic than An_{70} showed closer correspondence with the high- than with the low-temperature curves of Burri, Parker and Wenk (1967) and this is taken to indicate that these crystals are in a high to high-intermediate structural state. The recognition of a high structural state in the plagioclases more sodic than An_{70} is regarded in the present study only as the upper limit at which the optical orientation method allows the recognition of high structural state and not as a real transition in structural state.

The available field and petrographic evidence indicates that the Vididalur-Vatnsdalur rocks crystallized rapidly following their emplacement at high crustal levels and the plagioclases in these rocks are thus taken to have cooled rapidly before there was time for them to invert to a low structural state. This conclusion is supported by the generally immature character of the inversion and exsolution textures in the pyroxenes where such textures are developed (see p. 498), and the abundant interstitial glass in the basic rocks.

The cloudy sodic plagioclases with low structural state in the MU granophyre and the H_G rock (see Fig. 88) are believed to be types whose inversion and unmixing was possibly aided by a high volatile content in the surrounding magma in the same fashion as the sodic plagioclases of the intermediate and acid granophyres of the Skaergaard intrusion (Gay and Muir, 1962).

The composition of the plagioclases in the First and Second Phase intrusive rocks is shown diagrammatically in Chart 2 (see inside cover) which summarizes the optically determined compositions given in Part 1 of the Appendix.

(a) THE FIRST PHASE ROCKS: 1. Basic Rocks

Eucrites and cone-sheets

The most calcic plagioclases encountered in the rocks investigated were found in the eucrites and early set cone-sheets, which bear large euhedral to subhedral phenocrystals with faintly zoned cores of bytownite-anorthite in the compositional range An_{90} to An_{80} (see Chart 2, inside back cover). These crystals range up to 8 mm in size, are commonly of near-equant form with some tendency towards flattening in the (010) plane, and most of the crystals examined were found to have broad mantles of more sodic plagioclase zoned from near An_{79} to rims in the range An_{51} to An_{44}. (see Fig. 53a). These mantles make up between 10 and 60 per cent of the width of individual crystals, and commonly form 75 per cent of the total volume of these crystals. Little evidence of resorption was seen at the edges of the bytownite core portions of these large mantled crystals and the more sodic mantle material appears to be a continuous over-growth in most of the examples examined; a few crystals, however, showed sharp regular reversed zones between core and mantle and also a few thin shadowy reversals in the predominantly normal zoning of the mantles. The straight discontinuities between core and mantle reveal the outline of original euhedral crystals of bytownite-anorthite and this is taken to indicate that the cores are true original cumulus crystals. (Wager et al., 1960; Wager and Brown, 1968).

The mantles of the large crystals were found to show high-temperature optics for compositions more sodic than An_{70}. Determination of the structural state of the bytownite-anorthite cores of these crystals proved impracticable by optical orientation methods (see p. 463).

The portions of the mantles more sodic than An_{70} were often seen to enclose small groundmass pyroxene and plagioclase crystals in the eucrites and cone-sheets.

A small number of plagioclase phenocrysts up to about 1-2 mm in length were seen in the eucrites and cone sheets; these have core compositions of up to An_{75} to An_{79}, and do not show the almost unzoned core characteristic of the larger crystals but are continuously zoned over the same range as the mantles of the larger crystals. These smaller crystals are felt to have been precipitated at the same time as the innermost part of the mantles to the larger crystals and are for the present termed microphenocrysts.

A few crystals of still smaller size than these microphenocrysts were found in the eucrites and abundant crystals of this type form the groundmass of the cone-sheets; these crystals show lath sections and their maximum core composition lies at about An_{68}. These small groundmass crystals show continuous normal zoning over the same range as the outermost parts of the microphenocrysts and the mantles to the large crystals, and were found to have high-temperature optics in all but a few cases. Some of these groundmass crystals were found to have core compositions as sodic as An_{42}, and the rims of these small crystals are commonly of An_{30} plagioclase.

The presence of these three main types of plagioclase crystals in the eucrites and cone-sheets suggests that crystallization of plagioclase was an essentially continuous process which began a considerable time before emplacement of the basic material. The presence of distinct zoned mantles to the almost unzoned bytownite cores is taken to suggest that the original bytownite crystals were subjected to a sudden change in physical conditions which accelerated the rate of precipitation of plagioclase and thus caused rapid changes in the composition of the original liquid. The extremely rare evidence of resorption of these bytownite crystals evidences the rapidity of this change in conditions.

The balance of evidence is felt to indicate that these bytownites began crystallization in a tranquil environment at depth and were suddenly rushed upwards to a cooler level of the crust; during this passage more sodic plagioclase was precipitated both as separate microphenocrysts and as new zones mantling the cumulus bytownites. The evidence of the chilled eucrite margins indicates that crystals of all three main types had been precipitated by the time of emplacement of the eucrite. Crystallization subsequent to emplacement resulted in the formation of the most sodic plagioclase as groundmass crystals and outermost mantle zones. The rapid growth of the labradorites in the eucrite and cone-sheets is further evidenced by their high-temperature structural state, which indicates that the mantles and smaller plagioclase crystals were formed under essentially volcanic conditions.

Some of the bytownite phenocrysts in the eucrites and cone-sheets were seen to contain minute inclusions of ore, ferromagnesian material, and occasional glass, which are usually arranged parallel to the cleavages and outlines of the plagioclase; similar phenocrysts were also seen to be present in the eucritic inclusions found in the early set cone-sheets. Other bytownite crystals in the eucrites and cone-sheets were seen to be free from these small inclusions. Carmichael (1964) has noted the occurrences of similar inclusion-bearing bytownite phenocrysts in the basaltic rocks of Thingmúli, eastern Iceland; he suggests that the clear crystals "may represent true phenocrysts, rather than possible cognate xenocrysts of similar composition" (Carmichael, op. cit., p. 438).

The largest plagioclase crystals seen in the Vididalur eucrites and cone-sheets are very similar in composition and general structure to large plagioclase crystals described from the lavas and intrusions of eastern Iceland by Carmichael (1964), Blake, (1966) and Annels (1967), which also have bytownite cores and labradorite margins.

Similar bytownite crystals have been described from tholeiitic basalt lavas dredged from the Mid-Atlantic Ridge in the area of the Confederation Peak volcano, by Aumento (1968); these plagioclase crystals have cores of An_{86} and some show rounding and perforation due to resorption. These large crystals rest in a groundmass of small An_{65-70} plagioclases and are rimmed by thin zones of similar composition. Aumento (op. cit.) suggests that the bytownite crystals began crystallization in a large cupola below the Confederation Peak volcano from a liquid of composition approaching An_{65}. "In the subsequent extrusive process, the rising magma carried with it the contents of the upper part of the cupola, including the An_{86} plagioclase and smaller amounts of olivine and pyroxene. The rising magma would be affected by a sudden release in pressure, and a somewhat slower drop in temperature. The pressure drop would cause superheating of the magma and resorption of the plagioclase crystals. As the temperature dropped resorption would stop and crystallization commence, with the formation of olivine at 1340°C and plagioclase at 1260°C. Due to the then rapid cooling, only small crystals would develop and these would be of composition similar to the remaining bulk of the magma. Hence the plagioclase crystallized in the An_{65-70} range, both as new microlites and as rims around the previously resorbed crystals" (Aumento, op. cit., p. 9). These large resorbed bytownite crystals are interpreted by Aumento as cognate xenocrysts and the bytownite crystals in the Vididalur eucrites and cone-sheets are interpreted similarly, although in their case precipitation of plagioclase was an essentially continuous process not interrupted by resorption.

The presence of loose crystal aggregates and small crystal clusters of eucritic texture and mineralogy in the early basic cone-sheets of Vididalsfjall has already been mentioned, (p. 322); in these clusters the plagioclase crystals commonly show only a small range of zoning within the bytownite range, the more sodic rim compositions being generally confined to the rims of crystals at the periphery of the crystal clusters. These bytownite crystals are similar in general properties to the large single bytownite crystals seen in the cone-sheets and eucrites and are often intergrown with augite and olivine; ore grains were found to be rare in these clusters and the clusters have thus been interpreted as being the earliest products of crystallization of the eucritic liquid. The unzoned character of the plagioclase crystals within the clusters is taken to suggest that these clusters represent unconsolidated portions of a primitive or parent rock entrained by the cone-sheets as they passed through or from the body of slowly crystallizing eucritic material; the apparently near-contemporaneous formation of the eucrites and Type 1 and 2 cone-sheets indicated by field relationships is felt to suggest that these rocks may have proceeded from the same source, and the presence in both types of the large bytownite crystals suggests a common origin in a magma body accumulative in plagioclase. The eucrite inclusions are thus interpreted as cognate xenoliths formed during the earliest stages of crystallization of the eucritic liquid, which was later intruded as the eucrite bodies and early set cone-sheets. Although no direct connection between the First Phase eucrites and cone-sheets was seen in the Vididalur-Vatnsdalur area, a relationship of this type has been described from the Hornafjördur area by Annels (1967), and the Vididalur examples may originally have been similarly related.

Inclusions or xenoliths rich in bytownite-anorthite plagioclase were described from the Tertiary tholeiite dykes of northern England by Holmes and Harwood (1929) who concluded that the crystals were produced at an early stage from the parent magma of that which later gave rise to the enclosing rock; these authors postulate crystallization in a tranquil magma basin as the origin of the bytownite-anorthite crystals with subsequent removal to and in emplacement at a higher level as cognate xenocrysts suspended in more sodic tholeiitic material. Some of the singly occurring xenocrysts were found to have rims zoned out to compositions of An_{50} to An_{30}; there is a compositional break between these rims and the cores and Holmes and Harwood (op. cit., p. 44.) suggest that "factors at present unknown must have been involved to make possible the sudden break in composition between the original anorthite and the zoned rim." It seems likely that the break occurred as a result of the process postulated by Aumento (1968), and these examples from the north of England and the Mid-Atlantic Ridge are mentioned here due to the striking similarity they show to the examples from Iceland.

Holmes and Harwood (op. cit.) also record the presence of smaller phenocrysts of plagioclase in tholeiites bearing large anorthite xenocrysts; these have a core composition near An_{75} and are interpreted as the true phenocrysts precipitating from the xenocryst-charged magma; the Vididalur microphenocryst types are felt to be analogous types and to represent the most calcic phase to precipitate from the eucritic liquid in which the bytownite crystals were suspended.

Gabbros.

These rocks contain plagioclase of more sodic composition than that in the eucrites and the core compositions of the gabbro plagioclases lie within the range An_{69} to An_{41}, most rocks bearing crystals in the range An_{65} to An_{50}; these crystals were found to show high-temperature optics, and are thus believed to have crystallized under high-level conditions. The majority of the gabbro plagioclases examined were found to show normal continuous zoning over a considerable compositional range (see Chart 2); the greatest compositional change was found in the narrow marginal zones of these crystals, the outermost rims being as sodic as An_{34-36} in the case of the Hólar-Skessusaeti and Steinsvad gabbros. No sharply defined cores were seen in any of these crystals, and the gabbro plagioclases were seen to show more obvious flattening parallel to (010) than the bytownite crystals in the eucrites and cone-sheets. The twinning patterns of the labradorites are similar to those shown by the bytownites, with twinning developed mainly on albite, Albite-Carlsbad and Carlsbad laws with some pericline twinning. The labradorites range up to lengths of 30 mm in the coarser parts of the Urdarfell gabbro, some parts of this rock bearing exceptionally large crystals up to 70 mm in length; lengths of 5-10 mm are more typical of the bulk of the gabbro fabrics. Few of the gabbro labradorites were found to contain the minute ferromagnesian, ore and glass inclusions found in the bytownites of the eucrites and cone-sheets.

The bulk of the labradorite crystals observed in the gabbros are thought to be cumulus crystals which had already grown to a considerable size by the time of emplacement of the intrusions; the large labradorite crystals in the Urdarfell gabbro were seen to be broken in the marginal parts of the intrusion and this is felt to indicate that they had been transported some distance after the formation of the main part of the crystal. Evidence of the existence of labradorite cumulates beneath Vididalsfjall is given by the presence of loose crystal aggregates of this mineral in association with augite and ore mineral as inclusions in the early set cone-sheets (see Fig. 59b); these labradorite crystals are not strongly zoned and are believed to be cumulus crystals precipitated from a more sodic liquid related to the liquid from which the eucrites crystallized. The composition of these xenocrystal labradorite crystals was found to lie in the range $An_{69.5 - 66.5}$, which is rather more calcic than that of most of the gabbro crystals examined.

The more sodic labradorite-andesine crystals seen in the marginal dolerite and schliere of the Holar-Skessusaeti multiple intrusion show some tendency towards prismatic habit, with elongation along the "c" axis; these crystals are twinned mainly on albite, Albite-Carlsbad, and Carlsbad laws, and a few individuals showed Baveno twins. These crystals show strong continuous zoning to margins of An_{36}, and the most calcic core composition obtained for the marginal dolerite plagioclase phenocrysts was $An_{64.5}$. One crystal with a core composition of An_{75} was found in this rock, and it is possible that this is a xenocryst derived from the eucrite. The small groundmass plagioclase laths in this rock were found to be zoned from An_{58} to An_{36}.

The most sodic phenocrysts encountered in gabbroic rocks were found in the Vi 575/6 schliere of the Hólar-Skessusaeti marginal dolerite; these crystals have maximum core compositions of An_{55} and some of the smaller phenocrysts were found to have core compositions of andesine (An_{42}). These very sodic phenocrysts have high-temperature optics and are felt to represent the final feldspar phenocrysts to form from the gabbroic liquid which evolved from the original eucritic liquid.

Intermediate Rocks

The composition of the feldspars in the Urdarfell diorite overlaps with that of the plagioclases in the Hólar schliere and the similarities between the plagioclases in these two rocks are felt to suggest that these crystals may represent a late-stage labradorite-andesine cumulate derived from a final portion of the original eucrite-gabbro liquid series (see Figs. 56 and 70). The plagioclase crystals in the diorite show strong continuous normal zoning with maximum core compositions in the range An_{53-40}, and were found to have high-temperature optics. These crystals have strikingly euhedral prismatic form with elongation parallel to the "c" axis, and often reach lengths of 4-5mm, with a length to breadth ratio of 5 : 1. In the main facies of the diorite the continuous zoning is very pronounced and the greatest compositional change is seen to occur in the outermost 10 per cent of the width of the crystal, the rims having a composition of An_{21} (see Fig. 71a). Twinning in these crystals is usually of a simpler pattern than that seen in the gabbro labradorites, and is developed on albite, Albite-Carlsbad, and Carlsbad laws with some pericline twinning. A number of crystals in the main facies of the diorite have rounded outlines indicative of corrosion (see Fig. 72).

Some of the plagioclase crystals in the diorite were seen to be fractured and this fracturing is felt to have occurred during movement of cumulus crystals from their point of origin to their present position. The oligoclase rims of some of the diorite plagioclases were seen to be cloudy in contrast to their clear cores, and this may be due to incipient albitization due to reaction with the acid mesostasis of the diorite; this clouding is more noticeable in the basic granophyre hybrid rocks (H_I) in which the large columnar plagioclases are zoned from cores of high-temperature andesine (An_{46}) to rims of sodic oligoclase (An_{14}). In these H_I rocks the highly-zoned plagioclase rim is broader than in the diorite and the outermost part is seen to be corroded in both rock types, often showing subhedral outlines (see Fig. 76) and occasional embayments; the graphic acid mesostasis in these rocks is seen to rest with discontinuity against the corroded and resorbed cloudy rim of the plagioclase. This discontinuity is often only visible under high-power magnification, and indicates the essentially xenocrystal nature of the plagioclase crystals in the hybrid rocks.

The plagioclase crystals in the Urdarfell diorites and hybrid rocks are very similar in composition and general textural features to the phenocrysts described from the hybrid rocks associated with the Slaufrudal stock in eastern Iceland (Beswick, 1965); these Slaufrudal plagioclases are zoned from clear cores of andesine (An_{40}) to rims of oligoclase (An_{20-25}) which may be corroded and surrounded by mantles of cloudy alkali feldspar. In addition, most of the Slaufrudal andesine-oligoclase crystals are seen to be fractured.

Acid Rocks

The most calcic plagioclase crystals found in any of the First Phase acid rocks were seen in the Breidabólsstadur pitchstone, which bears euhedral phenocrysts with clear cores of high-temperature andesine (An_{42}) zoned with a few thin oscillatory zones to rims of oligoclase (An_{21}). These crystals show very simple twinning patterns on albite, Carlsbad, and Albite-Carlsbad laws, many crystals having no more than two twin individuals. The crystals are of similar compositional range to the xenocrysts in the intermediate and hybrid rocks and appear to be of unusually calcic composition for an Icelandic acid pitchstone; the composition of these phenocrysts is similar to that of the plagioclase phenocrysts from the andesites of Thingmúli described by Carmichael (1964, 1967a) which are weakly zoned andesines of composition An_{40-45}. The Thingmúli andesines are accompanied by phenocrysts of hypersthene and rare ferroaugite, and phenocrysts of hypersthene and ferroaugite are also found in the Breidabólsstadur rock, which thus has a phenocryst assemblage more typical of an andesitic than a rhyolitic rock. A few of these andesine crystals were seen to have small irregularities in outline which may be due to corrosion and thus indicative of disequilibrium. These andesine crystals are usually elongated parallel to the "c" axis with near-equidimensional cross-sections; similar high-temperature andesine crystals with core compositions of An_{41} were found as scattered

Table 8

OPTIC AXIAL ANGLES AND COMPOSITIONS OF PLAGIOCLASE PHENOCRYSTS FROM ACID ROCKS

(Plotted in Fig. 87, all measurements made on single crystals)

Rock Type	Specimen number	$2V_{\alpha}$	Composition (mol. % An)
pitchstone	Va 35	93	40
	Vi 178	75.5	30
		73	23
Dacite	Vi 172	77.5	31.5
		74	31.5
		81	31
		78	31
		72	30
		75	28
	Vi 201	82	31
		70	31
	Vi 200	81	29.5
Felsite	Vi 33	64.5	22
	Vi 39	76.5	30
	Vi 409c	73	20
Granophyre	Vi 174	75.5	27
		60	19
		60	17
	Vi 38	86	29
	Vi 40	89.5	30
		100	12
		86.5	10
		94.5	4
	Vi 262	91.5	1
	A 9	91.5	32
Granitic hybrid (H_G)	Vi 615	89	5

See (Appendix, Part 1) for key to location of specimens.

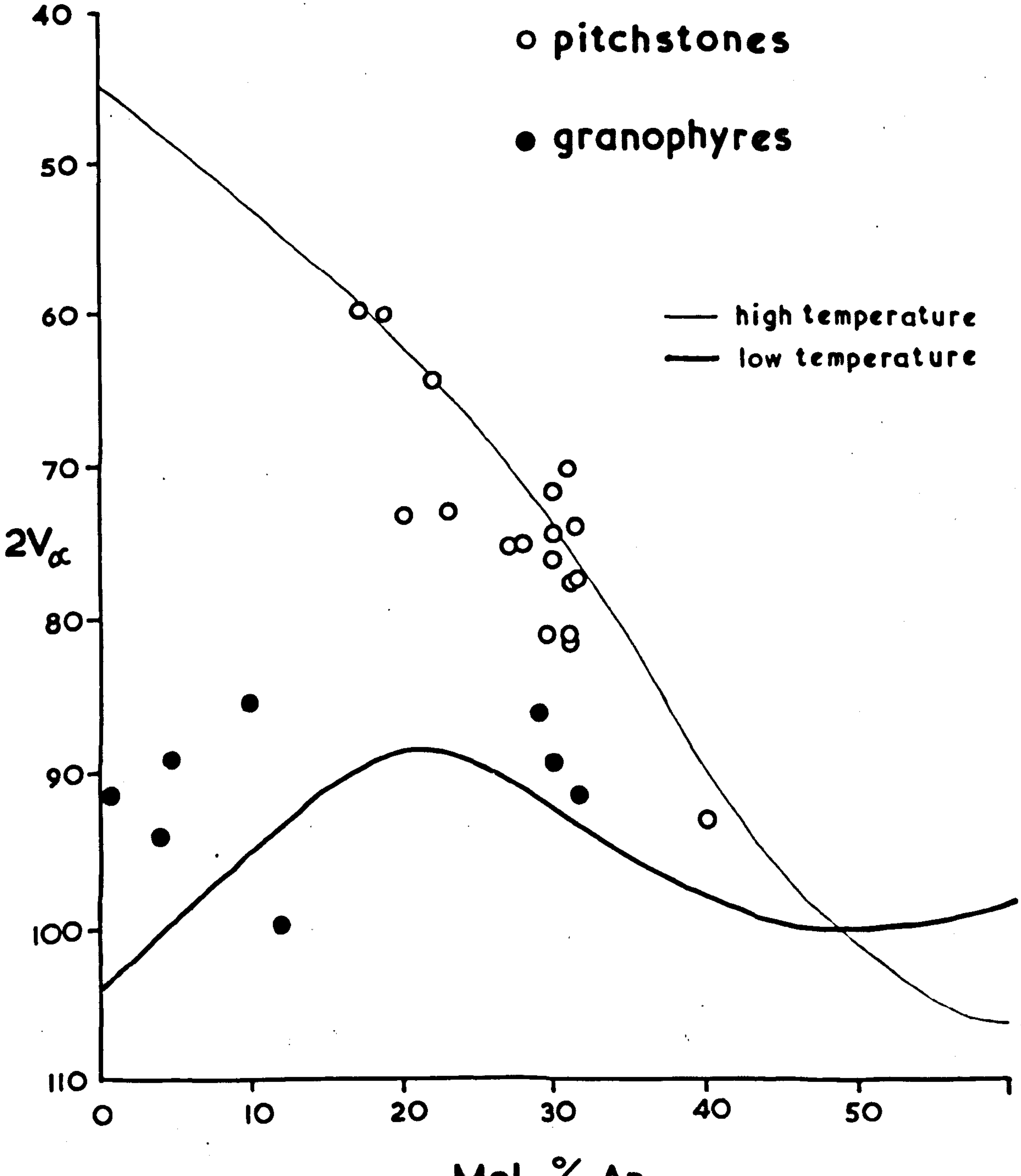


Fig. 87. Structural state of the plagioclase phenocrysts from the Vididalur-Vatnsdalur acid intrusions, showing the high-temperature optics of the phenocrysts in the minor intrusions (empty circles) and the low-temperature optics of those from the granophyres (solid circles). The points are plotted from the data of Table 8, and the two curves are taken from Slemmons (1962, Fig. 3).

<u>Table 9</u>

OPTICAL PROPERTIES AND COMPOSITIONS OF PLAGIOCLASES FROM THE FIRST PHASE COARSE-GRAINED ACID ROCKS (See Fig. 88).

Specimen number	Crystal type	Köhler angles			Twin law	R. I.	λ	ϕ	$2V_\alpha$	Composition	
		$\alpha\alpha'$	$\beta\beta'$	$\gamma\gamma'$						U-stage	R. I.
Granophyres											
Vi 38	p	175	34½	146½	Ab-Ala		+1½	+19½		32	
	p	176½	31½	150	Ab-Ala		-2	+15½		26	
Vi 40	p	174	31	150	Ab-Ala		+1	+15½	89	30	
	p	33	149	172	Ala		+76½	- 2½	99	12	
	p	148	37	173	Mb		-18	- 4	85	10	
Vi 262	p	156	38½	153	Mb		-15	-13½	91	0-5	
	p	....	....	....	....	β =1.535 1.539	....	....	....	....	7-15
A 9	p	174½	34	148½	Ab-Ala		0	+17½		30	
	p	178	32½	148	Ab-Ala		+2	+16½	91	31½	
Hybrid (H_G)											
Vi 615	p	133½	56½	148½	Cb		+25	+15		27	
	p	29	154½	168	Ala	γ'=1.534	+79½	- 6½	89	5	5
	p	161½	35	150	Cb		+11	-17		5	

The feldspar phenocrysts in the holocrystalline interior of the 50-degree sheet show a more extended range of zoning than those in the margins and the outermost zones of these crystals were found to have compositions of An_{14}. The groundmass plagioclases in this rock were found to have core compositions of near An_{20} and are zoned with apparent continuity into alkali feldspar which forms a continuous mantle round the crystals and is usually intergrown with quartz in extremely fine-grained graphic texture. This complete transition from sodic plagioclase to alkali feldspar is to be expected from the crystallization course of sodic plagioclase outlined by Muir (1962) and discussed with special reference to Icelandic one-feldspar acid liquids by Carmichael (1963b) and indicates that the 50-degree sheet liquid underwent strong fractionation during the final stages of its crystallization.

In the Raudkollur felsite, believed to have been connected to the 50-degree sheet, the plagioclase phenocrysts were found to have yet more sodic cores of high-temperature oligoclase (An_{22}) which show even zoning towards alkali feldspar compositions.

The twinning pattern in all these Raudkollur rocks was found to be simple for the andesines, and to be mainly on albite, Albite-Carlsbad and Carlsbad laws; in the more sodic phenocrysts the twinning pattern appears to be more complicated, and closely-spaced lamellar twins are more abundant.

Andesine phenocrysts are common in the Dalsá felsite, whose emplacement immediately preceded that of the MU granophyre, and these have cores of high-temperature An_{33} zoned to compositions of near An_{20}; these crystals show a simple twinning pattern on the same laws as the phenocrysts in the 50-degree sheet, many crystals having only two twin individuals.

The high-temperature structural state of the plagioclases in these fine-grained acid rocks discussed so far is shown in Fig. 87 in which the molecular weight per cent anorthite in a number of crystals (determined by optical methods) has been plotted against the optic axial angle using the data of Table 8; the optic axial angle is a very sensitive indicator of structural state in the more sodic plagioclases (Slemmons, 1962, Fig. 3).

The composition of these andesine phenocrysts in the fine-grained acid rocks of the Vididalur-Vatnsdalur area is similar to that of the plagioclases in the similar Tertiary acid rocks from Thingmúli (Carmichael 1964) and the acid cone sheets of the Setberg area (Sigurdsson, 1966). The Thingmúli rhyolites and acid pitchstones were found to contain high-temperature andesine phenocrysts with compositions of An_{30-35}. (Carmichael, op. cit.).

The MU granophyre was found to contain phenocrysts of andesine with core compositions of An_{32-30} (see Fig. 87, Table 8, and Fig. 88, Table 9); these crystals have more complex twinning patterns than those in the fine-grained acid minor intrusions, with closely-spaced lamellar albite and pericline twinning, and were found to have high optic axial angles ($2V_\alpha = 80 - 90^\circ$ in many cases). Comparison of these values of $2V_\alpha$ and composition with the curves of Slemmons (1962) indicates that these feldspars are in a transitional to low structural state (see Fig. 87), and a similar structural state is indicated by the positions of the plotted twin axes of these feldspars relative to the twin-axis migration curves for high- and low-temperature plagioclase given by Burri, Parker and Wenk (1967). This data is set out in Table 9, and plotted in Fig. 88.

These granophyre plagioclases were found to be continuously zoned to rims of alkali feldspar in similar fashion to the groundmass feldspars in the interior of the 50-degree sheet, and the continuous alkali feldspar rims are invariably intergrown in graphic texture with quartz. The zoning is difficult to trace with precision in these crystals as the cores of the phenocrysts are clear but their outer parts are turbid. This turbidity is believed to be due to the unmixing of the marginal sodic feldspar parts of the crystals; low-temperature plagioclases in the range An_5 to An_{25} are known to consist of sub-microscopic intergrowths of sodium-rich and calcium-rich regions (Deer, Howie and Zussman, 1965, Vol. 4, p. 96) and it seems likely that unmixing of these two components would be aided by the volatile-rich nature of the MU granophyre magma. The proportion of the

Granophyre Plagioclases

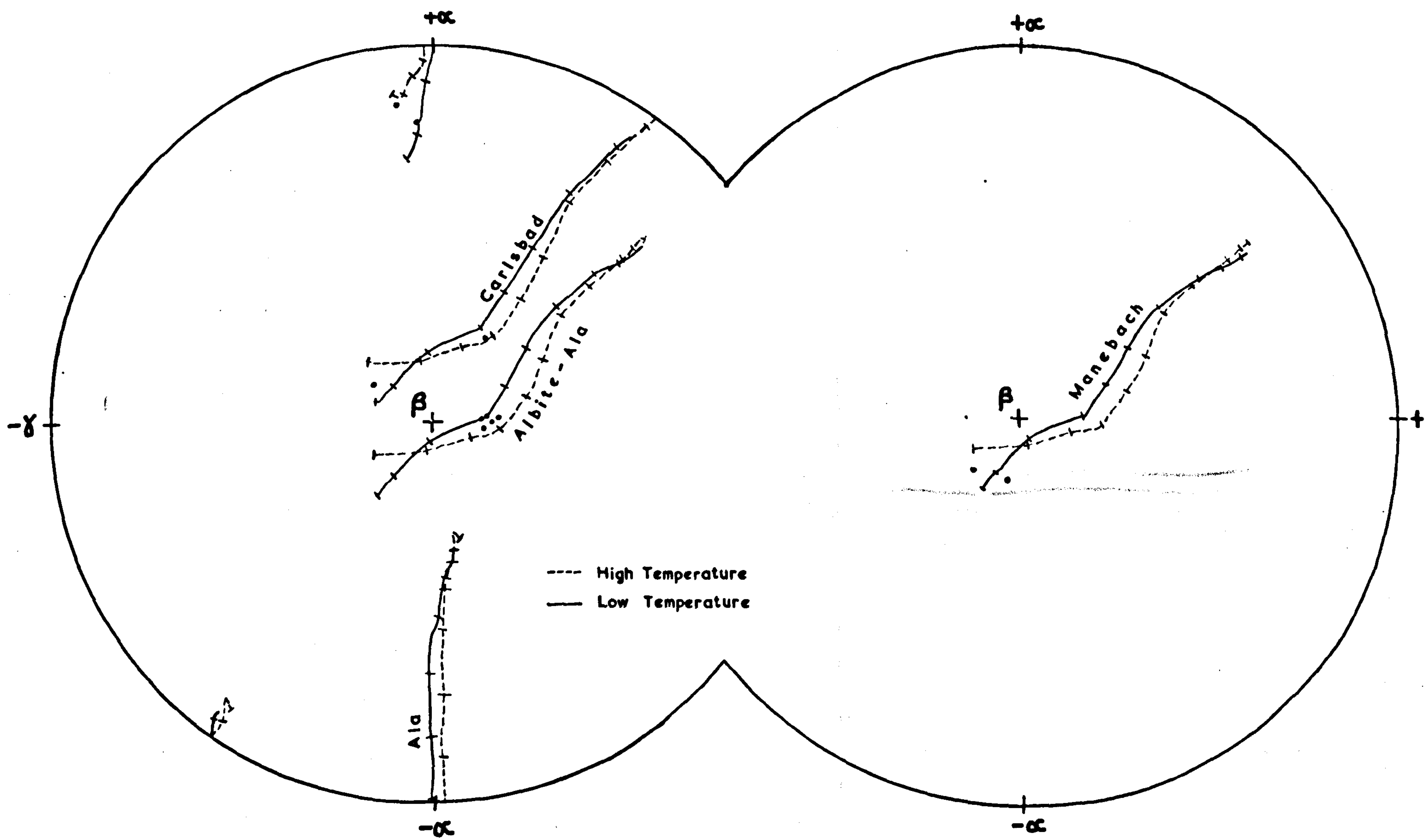


Fig. 88. Stereogram of the position of the twin-axes (black dots) of eleven sodic plagioclase phenocrysts from the coarse-grained Vididalur acid rocks, showing the low to transitional optics of these crystals. The points are plotted from the data of Table 9; the migration curves are taken from Burri, Parker and Wenk (1967).

individual plagioclase crystals clouded in this way was seen to be dependent on the size of the individual phenocrysts, the clouding being restricted to the outermost, more sodic parts of the largest crystals and being complete in the smallest crystals.

The most sodic plagioclases in the Vididalur-Vatnsdalur rocks were found in the granitic H_G hybrid rock and in parts of the MU granophyre; these crystals were found to have core compositions of transitional to low-temperature albite in the range An_{0-12}, and the high potash content of these rocks would appear to indicate that these feldspars may in fact be anorthoclases. This is, however, thought to be unlikely as the optic axial angles of these feldspars were found to lie in the range $2V_\alpha = 80 - 90^\circ$ (see Table 8, Fig. 87) and anorthoclases generally have lower optic axial angles in the range $2V_\alpha = 38.9\text{-}57.6^\circ$ (MacKenzie and Smith, 1956). These very sodic plagioclases in the MU granophyre show complicated twin patterns, are often near-equidimensional in cross-section and are surrounded by graphic intergrowths of alkali feldspar and quartz; the alkali feldspar in these intergrowths is optically continuous with the most sodic outer zones of the plagioclases and this is a further example of strong fractionation along the crystallization course discussed by Carmichael (1963b) for the case of one-feldspar Icelandic acid rocks.
A few scattered phenocrysts of andesine-oligoclase were found in the H_G granitic hybrid rocks; the zoned rims of these crystals were seen to be of irregular form with corroded margins and to

be clouded near their junctions with the discontinuous alkali feldspar mantles. These crystals show the same general range of zoning as the large andesine crystals in the diorite and basic granophyre (H_I) hybrid rocks and the central portions of these crystals have similar euhedral columnar shape to the crystals in the intermediate rocks, so that they are taken to be xenocrysts derived from the diorite. These andesine-oligoclase crystals were found to form about 7 per cent by volume of the H_G rock.

(b) THE SECOND PHASE ROCKS

The compositional range of plagioclase types found in the Second Phase rocks is similar to that found in the First Phase rocks, and the main phenocryst types found in First Phase rocks can be matched with similar Second Phase types; however, phenocrysts of labradorite-andesine and turbid sodic plagioclases typical of the diorite, hybrids and granophyre of the First Phase were not found in any of the Second Phase rocks. The plagioclases seen in the Second Phase rocks show similar compositions to those of the minor intrusions of the First Phase, which may explain the apparent simplicity of the range of Second Phase plagioclases; it seems possible that plagioclases of similar type to those of the First Phase coarse-grained intermediate to acid rocks may exist in similar Second Phase rocks concealed at depth.

1. Basic Rocks. Eucrites and Cone-sheets.

The most calcic plagioclases found in Second Phase rocks occur as large euhedral crystals up to 6 mm in length in the Skessusaeti summit eucrite intrusion and the late set cone-sheets. These crystals have faintly zoned cores of composition An_{90-80} which may bear small, sometimes oriented, inclusions of ferromagnesian material, ore or glass in the same way as the First Phase phenocrysts, and as in these crystals the cores are surrounded by broad continuous mantles of progressively more sodic plagioclase zoned to margins of andesine (An_{46-38} in the eucrite and Type 2 sheets, An_{32} in the Type 1 sheets) see Fig. 79a and 81a); as in the First Phase bytownite crystals, these mantles may make up 75 per cent by volume of a given crystal, and their growth is paralleled by that of discrete micro-phenocrysts with An_{75-78} cores.

The mantles of the bytownite crystals were found to show high temperature optics and they can be seen to enclose small groundmass crystals of plagioclase, pyroxene and olivine. The crystals are twinned on albite, Albite-Carlsbad, Carlsbad and pericline laws and show some tendency toward stumpy tabular form, with some flattening in the (010) plane.

The groundmass plagioclase crystals were found to have core compositions in the range An_{68-40}, the lower values being typical of the Type 1 and 3 cone-sheets; the zoning range of the groundmass crystals was found to coincide with that of the outermost parts of the two larger crystal types, and they were seen to be intergrown in poikilophitic texture with augite in the same fashion as the groundmass crystals of the First Phase rocks.

The general composition, morphology and textural relationships of the plagioclase crystals in the eucrite and late set cone-sheets are so similar to those of the plagioclases in the corresponding First Phase rocks, that these Second Phase crystals are taken to be of a similar mode of formation. The occurrence of small eucritic clusters of bytownite, augite and olivine in the Type 1 late set cone-sheets and in the Skessusaeti composite Type 1/Type 2 sheet evidences that the two rock types were of simultaneous availability and this is felt to suggest that the eucritic inclusions and large bytownite crystals represent cognate inclusions derived from sites of bytownite accumulation in the same way as those of the First Phase rocks (see pp. 470-71).

Gabbros

The only gabbro intrusion of Second Phase type found was that forming the Hnjúkur plug, and the coarse-grained rock of the plug core is accumulative in labradorite plagioclase; these plagioclase crystals were found to have cores of high-temperature labradorite zoned with several tens of extremely thin shadowy discontinuities to rims of andesine (An_{40}). These crystals are particularly distinctive in that they are of tabular form with marked flattening parallel to (010) and are commonly 9 x 4 x 2 mm in size. Smaller crystals showing lath sections are also present in this rock; these have more sodic compositions in the labradorite range, and are often seen to be poikilophitically enclosed by augite grains.

The tabular labradorite crystals are similar in form, composition and zoning characteristics to labradorite phenocrysts found in the TFB group lava flows in Vatnsdalsfjall (see Chart 2), and they are thus believed to be of common origin.

Labradorite phenocrysts were found to be present in the more olivine-poor Type 1 and 3 late set cone-sheets and bodies such as the Hjallin lens, which bear small tablets with high-temperature An_{69-64} cores zoned to andesine rims which enclose small groundmass plagioclase laths and augite grains. These phenocrysts are twinned on albite, Albite-Carlsbad, Carlsbad and pericline laws, and it seems likely that accumulation of similar crystals in a high-level environment resulted in the formation of rocks such as the Hnjúkur gabbro; the plug structure and discontinuously zoned high-temperature plagioclase phenocrysts of the Hnjúkur gabbro intrusion are felt to indicate that accumulation of feldspar possibly took place within a volcanic conduit not far below the Second Central Phase ground surface.

No loose crystal aggregates of labradorite similar to those seen in the early set cone-sheets were found in the Second Phase basic rocks, and there is thus no direct evidence so far of the existence of labradorite cumulates in depth during the Second Phase. Xenoliths of medium-grained olivine-tholeiite exactly similar to the material forming the Type 1 late set cone-sheets were found in the Hjallin tholeiite lens, and these were found to be of labradorite tablets up to 2 mm in length; the textures of the xenoliths examined, however, indicate that they are of material which had already crystallized to completion before incorporation by the host rock, and the fine-grained tholeiite host material was not seen to invade the mesh of the xenoliths (see p. 434).

2. Acid Rocks

The most calcic plagioclase crystals found in the Second Phase acid rocks were the phenocrysts of the Krossdalur dacitic intrusion some of which were found to have cores of high-temperature andesine (An_{41});the bulk of the crystals examined, however, showed core compositions in the range An_{32-30} (see Table (e) ,Appendix Part 1) and the range of zoning of the crystals appears to be limited. The phenocrysts in this rock were found to be twinned on albite, Albite-Carlsbad and Carlsbad laws, there being often only two or three twin individuals in any given crystal; these crystals were usually found to show euhedral lath and tabular sections up to about 1.5 mm in length.

The more calcic andesine phenocrysts were seen to have slightly rounded outlines in section which are felt to be indicative of slight resorption; small glassy patches were found in the cores of some of these crystals and these may also be due to some disequilibrium in between phenocrysts and liquid.

The groundmass feldspar laths of this rock have oligoclase cores (An_{20}) which are zoned continuously to rims of alkali feldspar in the same fashion as the groundmass plagioclases in the First Phase acid minor intrusions.

The phenocrysts of the acid component of the Gálgagil intrusion were found to have core compositions of high-temperature An_{37-30} zoned to rim compositions of An_7 , and the form and twinning patterns of these crystals were seen to be exactly similar to those of the Krossdalur intrusion plagioclases. Smaller euhedral prismatic phenocrysts (up to 1 mm in length) with core compositions in the range An_{30-20} were found in this rock and these are interpreted as forming a continuous series of microphenocrysts and groundmass crystals. Two morphological types of crystal were distinguished in this series, one having hollow cores and showing annular sections perpendicular to the "c" - axis and the other having solid cores; the hollow-core crystals were found to be restricted to small rounded patches in the rock, (see Fig. 83a and b) and both types were found to have similar maximum core compositions of An_{30}.

4-3 ALKALI FELDSPAR

1. Basic Rocks

Alkali feldspar was found to be present in a large number of both First and Second Phase rocks representative of the entire range in silica content.

Small patches of extremely fine-grained felsitic material made up of minute turbid alkali feldspar grains were found in the final mesh gaps of the Hólar-Skessusaeti eucrite; in the early set cone-sheets and the Borgarvirki eucrite this feldspar was often seen to be in very fine-fret graphic intergrowth with quartz in the final mesh gaps. Similar graphic intergrowths were seen to be present in the final interstices of the Steinsvad and Urdarfell gabbros and these were too small for accurate optical measurements; they are taken to be of alkali feldspar by analogy with the similar larger-scale alkali feldspar-quartz intergrowths seen in the Vididalur-Vatnsdalur acid rocks.

Alkali feldspar-quartz intergrowths were also seen in the Second Phase basic rocks, and were found to fill occasional final gaps in the mesh of the Skessusaeti summit eucrite, the Hnjúkur core gabbro and the late set cone-sheets.

The occurrence of alkali feldspar-quartz residua is typical of tholeiitic basic rocks (Kennedy, 1933; Yoder and Tilley, 1962), and has been recorded in the gabbroic rocks of eastern Iceland by Cargill et al. (1928), and Annels (1967). The occurrence of such acid residua is usually taken to be the result of fractionation of tholeiitic material, but it seems possible that some of the Vididalur-Vatnsdalur occurrences, notably those in the Urdarfell gabbros, resulted from the incorporation of small amounts of already existing acid material; in the Urdarfell gabbro, small graphic quartzofeldspathic patches were seen to be developed near inclusions of basic granophyre (H_I) hybrid material (p. 405).

2. Intermediate Rocks

Graphic intergrowths of alkali feldspar and quartz of varying regularity and fret size were seen to be common in the diorite and H_I hybrid rocks; the feldspar in these intergrowths is turbid and was found to have $2V_\alpha = 72-79^\circ$ (Average value 75°, see Table 10). Values of $2V_\alpha$ greater than $30-40^\circ$ for alkali feldspars bearing more than 5-10 per cent of the albite component are typical of perthitic feldspars (Marfunin, 1962, pp. 94-95, Fig. 24.) The turbid appearance and relatively high $2V_\alpha$ of the feldspar component in these graphic intergrowths are thus taken to indicate that it is a cryptoperthitic type; the hybridization process has been shown to be due to mixing subsequent to the invasion of granophyre by diorite, and the alkali feldspar of the graphic material is thus thought to be a sodic type of similar composition to that in the MU granophyre. The graphic intergrowths in the diorite and hybrid rocks form discontinuous and incomplete mantles to the plagioclases and are thus not the result of continuous feldspar fractionation within a single liquid.

3. Acid Rocks. (a) Fine-grained types.

Alkali feldspar was found to occur in the fine-grained acid minor intrusions as outer zones to plagioclase phenocrysts, small discrete phenocrysts or as a groundmass constituent.

Direct measurements of the optic axial angles of a number of feldspar crystals were compared with these determined for sodic alkali feldspars investigated by chemical, X-ray and optical methods and the ranges obtained by three such investigations of anorthoclases are shown below :-

$2V_\alpha$ range	
$38.9 - 57.6^\circ$	MacKenzie and Smith (1956)
$41 - 48^\circ$	Carmichael (1960a)
$53.2 - 62.0^\circ$	Boudette and Ford (1966)

The maximum value in the range of Boudette and Ford (op, cit.) is near to the value obtained for oligoclases (An_{22}) in the 50-degree sheet, and the upper value of MacKenzie and Smith (op. cit.) has been adopted as the upper limit of high-temperature alkali feldspar $2V_\alpha$ values in this study; optically homogenous alkali feldspars with $2V_\alpha$ values lying in this range are referred to as anorthoclases where they occur in the Vididalur-Vatnsdalur rocks.

The plagioclase phenocrysts in the 50-degree sheet were found to be zoned continuously to rims of anorthoclase (average $2V_\alpha = 55^\circ$) from cores of high-temperature oligoclase (An_{22}, $2V_\alpha = 65^\circ$) and one similar crystal was found to have a rim of anorthoclase with $2V_\alpha = 52^\circ$. The outermost zones of the oligoclase phenocrysts in the Raudkollur felsite were also found to be of anorthoclase with $2V_\alpha = 54^\circ$ (average of four direct determinations in range $2V_\alpha = 50\text{-}57^\circ$).

Extremely fine-fret graphic intergrowths of quartz and alkali feldspar were found in the Raudkollur, Kornsá and Dalsá-Urdarfell felsites, and in the first two types these intergrowths form complete mantles continuous with the outermost zones of the groundmass oligoclase laths; the most sodic rims of this plagioclase were found to have compositions in the range An_{9-11}. This anorthite content is near to that of the anorthoclases from eastern Iceland analysed chemically by Carmichael (1960a, specimens 4F and 7F, Table III, p. 597) and it seems possible that the alkali feldspar of the intergrowths in the Vididalur-Vatnsdalur rocks is of similar composition to these examples.

The groundmass of the Dalsá-Urdarfell felsite consists of very small ragged grains of slightly turbid alkali feldspar which held a faint yellow stain after etching with hydrofluoric acid and treatment with sodium cobaltinitrite solution; turbid alkali feldspar similar to that present in the groundmass was also seen to form a thin rim to the andesine-oligoclase phenocrysts in this rock.

Thin zones of anorthoclase are believed to be present at the outermost rims of the plagioclases in the acid component of the Second Phase Gálgagil composite intrusion as these rims were found to have minimum compositions of An_7, which is a similar anorthite content to that of the anorthoclases from eastern Iceland (Carmichael, 1960a). Muir (1962) has described sodic plagioclases which are zoned continuously to rims of anorthoclase and the feldspars in the acid intrusions studied are believed to be similar to these examples.

Indirect evidence of potential anorthoclase in the Vididalur-Vatnsdalur acid minor intrusions is indicated by the normative data of the four fine-grained rocks analysed; the normative orthoclase, albite and anorthite of these rocks, when re-calculated to 100 per cent, plot in the anorthoclase field of a ternary feldspar diagram (see Fig. 93). In addition, the crystallization of anorthoclase has been shown to be characteristic of the later fractions of Icelandic one-feldspar acid liquids undergoing strong fractionation (Carmichael, 1963b) and the small $2V_\alpha$ of these feldspars is taken to indicate that they are of near-homogenous anorthoclase.

(b) <u>Coarse-grained types</u>,

Alkali feldspar was found in the MU granophyre in micrographic intergrowth with quartz (see pp.371-72, Figs. 67-69); the feldspar component of these intergrowths was seen to be continuous with the outermost zones of the plagioclase phenocrysts and this suggests that the mineral formed as the result of a high degree of fractionation in a one-feldspar acid liquid in the manner suggested by Carmichael (1963b). The formation of outer zones of alkali feldspar to these plagioclase phenocrysts is essentially similar to that seen in the outermost zones of the feldspar phenocrysts of the fine-grained acid rocks of the Vididalur-Vatnsdalur area (see p.491).

Most of the alkali feldspar was found to be of cloudy appearance and this is possibly due to unmixing of the sodic and potassic components of the alkali feldspar to form a perthite type. The $2V_\alpha$ values obtained for the feldspar of the phenocryst rims and graphic intergrowths were found to lie in the range 61-88^0, and this material is thus believed to be a cryptoperthitic type (see Table 10 and Marfunin, 1962, pp. 94-95, Fig. 24).

As in the case of the fine-grained acid rocks (p.493), the recalculated normative feldspar components of the analysed MU granophyre, H_G granitic rock and the Type 2 acid vein were found to plot in the anorthoclase field of a ternary feldspar diagram (see Fig. 93). This is taken to indicate that the alkali feldspar of these rocks is an anorthoclase and it is thus identified as an anorthoclase cryptoperthite.

Table 10

OPTIC AXIAL ANGLES OF ALKALI FELDSPARS FROM THE COARSE-GRAINED ACID AND HYBRID ROCKS OF THE VIDIDALUR-VATNSDALUR AREA

Rock Type	Specimen Number	$2V_\alpha$ range (degrees)	$2V_\alpha$ average value (degrees)	Number of crystals measured
MU granophyre	Vi 217	76-80	78	2
"	Vi 40	-	91	1
"	Vi 38	-	81	1
H_G granitic hybrid	Vi 615	61-82	77†	5
"	Vi 265/23	67-88	77	4
H_I basic granophyre hybrid	Vi 265/14	72-79	75†	7
Type 2 acid vein	Vi 212	41-50 59-71	46* 66*	7 6

* Crystal core

† Graphic material.

All other measurements were made on the rims of plagioclase phenocrysts.

TABLE 11

OPTICAL PROPERTIES AND COMPOSITIONS OF CLINOPYROXENE FROM THE VIDIDALUR-VATNSDALUR ROCKS

Number on Fig. 90	Specimen number (see Table in Appendix, Part 1)	Range of $2H_\gamma$ (degrees)	Average $2H_\gamma$ (degrees)	$2V_\gamma$	β	Composition Hess (1949) Muir (1951)	Carmichael (1960b)
1	Vi 556	50.1-54.3	52.9	50.6	1.690	$Ca_{42}Mg_{42.5}Fe_{15.5}$	-
2	Vi 95	50.8-52.3	51.3	49.8	1.693	$Ca_{41}Mg_{40}Fe_{19}$	-
3	Vi 575/7a	48.4-50.5	49.5	48.1	1.693	$Ca_{40}Mg_{40.5}Fe_{19.5}$	-
4	Vi 265/14	48.2-52.9	50.0	48.6	1.695	$Ca_{40}Mg_{39}Fe_{20.5}$	-
5	Vi 265/1	47.6-50.7	49.0	47.8	1.694	$Ca_{40}Mg_{39}Fe_{21}$	-
6	Vi 28	46.3-50.2	48.7	47.2	1.695	$Ca_{39.5}Mg_{39}Fe_{21.5}$	-
7	Vi 2	47.5-50.0	48.8	47.4	1.696	$Ca_{39.5}Mg_{38.5}Fe_{22}$	-
8	Va 33	44.2-48.2	46.7	45.2	1.697	$Ca_{38}Mg_{38.5}Fe_{23.5}$	-
9	Vi 320	44.7-52.6	49.0	47.5	1.697	$Ca_{39.5}Mg_{37.5}Fe_{23}$	-
9a*	Vi 85	47.6-51.5	49.5	47.8	1.698	$Ca_{39.5}Mg_{37}Fe_{23.5}$	-
10	Vi 398	46.6-52.6	49.9	48.4	1.697	$Ca_{40}Mg_{37}Fe_{23}$	-
11	Vi 76	44.4-50.0	46.6	45.2	1.699	$Ca_{38}Mg_{36}Fe_{26}$	-
12	A 14	56.0-60.0	57.7	55.5	1.714	$Ca_{44}Mg_{22.5}Fe_{33.5}$	$Ca_{48}Mg_{24}Fe_{28}$
13	Va 35	50.0-52.2	51.1	48.8	1.717	$Ca_{38}Mg_{24}Fe_{38}$	$Ca_{38.5}Mg_{27}Fe_{34.5}$
14	Vi 178	52.3-54.7	53.5	51.4	1.720	$Ca_{39.5}Mg_{21.5}Fe_{39}$	$Ca_{41}Mg_{24}Fe_{35}$
15	Vi 27	49.6-54.2	51.1	49.8	1.685	$Ca_{41}Mg_{47}Fe_{12}$	-
16	Vi 60	46.2-51.0	48.8	47.6	1.685	$Ca_{40}Mg_{47}Fe_{13}$	-

*Represented by point 9 on Fig. 90.

4-4 CLINOPYROXENES

The Nature of the Pyroxenes in the Vididalur-Vatnsdalur Intrusive Rocks

The pyroxenes in the Vididalur-Vatnsdalur rocks were found to show some features in common with the pyroxenes described from the tholeiitic series of the Skaergaard intrusion (Wager and Deer, 1939; Brown,1957; Wager and Brown, 1968) and the Thingmúli volcano (Carmichael, 1960b, 1964, 1967a). The most notable similarity is the frequent occurrence within the same rock of calcic augite and pigeonite, and this confirms the tholeiitic composition of the Vididalur-Vatnsdalur rocks. (Kennedy,1933; Yoder and Tilley, 1962). Pigeonite was identified in a large number of basic rocks as clinopyroxene which showed interference figures with very small $2V_\gamma$ or uniaxial character. Hawkes (1916a) noted the presence of enstatite-augite in the groundmass of a basalt from Iceland and Carmichael (1964) drew attention to the uniaxial to near-uniaxial clinopyroxene occurring as the outer margins of groundmass pyroxene grains or as independent groundmass grains in the Thingmúli basic lavas; Carmichael suggested that the relationship represented augite zoned to sub-calcic augite or pigeonite in similar fashion to the groundmass pyroxenes of the Hawaiian tholeiites. Further investigation of these Thingmúli groundmass pyroxenes using electron-probe analytical techniques confirmed the presence of pigeonite, and it was concluded that the groundmass augites were mantled by pigeonite possibly with a compositional break between the two types (Carmichael, 1967a); in the same paper, Carmichael states "It is possible that there is a gradational relationship, but if so, it is not detectable within the resolution of the (electron-probe) technique. ... it is assumed that two distinct pyroxene phases are present in all those rocks which contain a calcium-rich and a calcium-poor pyroxene, with a miscibility gap between them." (Carmichael, op. cit., p. 1817).

Pigeonite was found to occur in the Vididalur-Vatnsdalur rocks as rims to the groundmass augite crystals of the early and late sets of cone-sheets and as occasional independent groundmass grains in these rocks; no optical discontinuities were found between the cores and margins of grains mantled by pigeonite. Some of the large interstitial augite grains in the eucrites and gabbros were also found to have rims of pigeonite.

The interstitial augite grains in the eucrites and gabbros of both First and Second Phases were also found to show occasional extremely thin regular lamellae often of slightly lower birefringence than the bulk of the individual crystal; many of these lamellae were seen only under a high-power objective and they were invariably found to be oriented parallel to the (001) plane of the host crystal. More abundant lamellae of similar orientation were found in the augites of the Skaergaard intrusion by Brown (1957); these lamellae were shown by Brown (op. cit.) to be due to the exsolution of pigeonite in the manner suggested by Poldervaart and Hess (1951), and later X-ray work confirmed this suggestion (Bown and Gay, 1960). The lamellae parallel to (001) in the augites of the Vididalur-Vatnsdalur basic rocks are thus taken to be of exsolved pigeonite, by analogy with the Skaergaard types; these lamellae were never found to be such a penetrative feature as those described from the Skaergaard augites (Brown, 1957) and were usually found only in small numbers as widely spaced striations near the margins of the augite crystals. This apparent confinement of lamellae to the crystal margins of the eucrite and gabbro augites may be indicative of zoning of the augite toward pigeonitic rim compositions. Sigurdsson (1966a) has recorded the presence of fine lamellae in the augites of the Kolgrafamúli gabbro, Snaefellsnes, and has suggested that these are "possibly exsolution lamellae of differing composition to that of the host pyroxene" (op. cit., p. 86).

One large inverted subhedral pyroxene crystal 1 mm in length was found in the main facies of the Hólar-Skessusaeti eucrite; this was seen to consist of pale optically negative orthopyroxene with closely spaced (110) cleavages transverse to which were aligned numerous brightly birefringent blebs in trains parallel to (001) (see Fig. 89).

Fig. 89. A large inverted pigeonite phenocryst in the eucrite about 20 m above the lowest part of the Skessusaeti outcrop. Trains of small exsolved augite blebs // (001) can be seen to cross the closely-spaced (110) partings of the orthopyroxene host material.

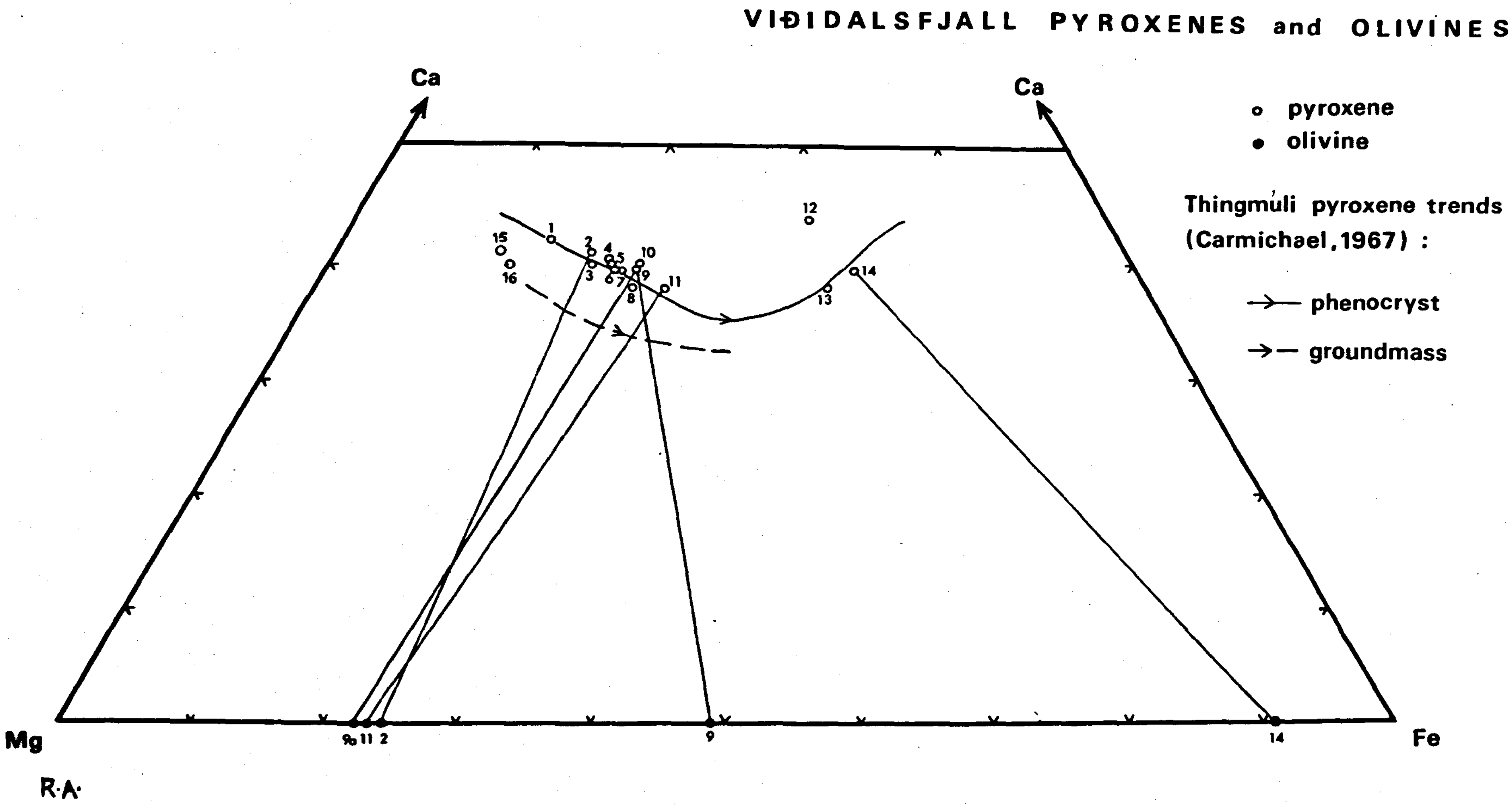
Cross-polarized light, x 100 (Speciment B 12a).

This crystal is taken to represent an early-formed crystal of pigeonitic clinopyroxene which began to exsolve augite but inverted to orthopyroxene. The blebby form of the exsolved augite is believed to be characteristic of the earliest stages of exsolution and this is interpreted as being due to a small temperature interval between crystallization and inversion of the original pigeonitic pyroxene, by analogy with the relationship deduced by Brown (1957) for the inverted pigeonites of the

Skaergaard intrusion; in the Skaergaard inverted pigeonites, the lamellae of exsolved augite are first seen as blebs which "become progressively more ordered and abundant with height in the layered series, and this is related to the progressive increase in the temperature interval between crystallization and inversion" (Brown, op. cit., p. 539).

The clinopyroxenes of the First and Second Phase intrusive rocks are discussed in the following pages with reference to Fig. 90 which is plotted from the data of Table 11; the numbering of the points on the diagram is that used in Table 11, individual pyroxenes being indicated in the text by numbers in parentheses. The plotted points cluster about the trend determined for the Thingmúli clinopyroxene phenocrysts by Carmichael (1967a).

Fig. 90. Optically determined compositions of clinopyroxenes and olivines from the Vididalur-Vatnsdalur intrusions. The Thingmúli clinopyroxene trends (Carmichael, 1967a) are shown for comparison. Plotted from the data of Table 11.



(a) THE FIRST PHASE ROCKS

1. Basic Rocks

The most magnesian clinopyroxene crystals found in the Vididalur-Vatnsdalur rocks were seen in the groundmass of the early basic cone-sheets; these crystals were found to have a composition of Ca_{40-41} Mg_{47} Fe_{12-13} (Nos. 15 and 16) which plots near to the Thingmúli groundmass trend of Carmichael (1967a). The grains were too small for distinct exsolution textures to be seen, and some rims and small discrete crystals of pigeonite were found in these cone-sheet groundmass augites.

A few of the early set cone-sheets on Ásmundarnúpur were seen to contain small acicular pink-brown augites in stellate clusters within small patches which are believed to be the result of crystallization under local volatile-rich conditions; similar acicular augites have been described from quartz-dolerite Talaidh-type late basic cone-sheets on Mull (Bailey et al., 1924, p. 302-303) and from the Permo-Carboniferous quartz-dolerites of the Midland Valley of Scotland (Falconer, 1908; Walker and Irving, 1928).

The augites seen in the small eucrite inclusions within the early set cone-sheets are of the same pale pink-brown type as those in the eucrite intrusions, and a few crystals in direct contact with the enveloping dolerite were seen to have very narrow rims of pigeonitic pyroxene. These rims were too narrow to assess whether or not they were continuous with the main part of the crystal, but they are continuous with the groundmass pyroxene and are taken to be overgrowths of pigeonite precipitated on to the nucleus afforded by the xenocryst during rapid cooling of the cone-sheet dolerite.

The pale pink-brown interstitial augite grains in the First Phase eucrite of the Hólar-Skessusaeti intrusion were found to be of slightly less magnesian composition than those of the early set cone-sheets ($Ca_{42}Mg_{42.5}Fe_{15.5}$, No. 1), and were seen to contain a few very narrow pigeonite lamellae oriented parallel to (001); many of these augite grains were seen to be twinned parallel to (100) and to have extremely narrow rims of optically continuous pigeonite.

The composition of the augite in the Borgarvirki eucrite was not determined and this mineral forms crystals of rather more euhedral form than those seen in the other eucrites; a faint zonation was seen in the augites of this rock between crossed polars, but no pigeonitic pyroxene was detected at the crystal margins and the zoning may be due to variation in iron and magnesium within the pyroxene.

The groundmass augite of the fine-grained marginal eucrite at Hólar was found to have $2H_{\gamma} = 54.7^{\circ}$ (average of range $2H_{\gamma} = 51.2-58.1^{\circ}$) and this high value indicates that it is a very calcic type; rims of pigeonite were found in these crystals and small independent grains of near-colourless pigeonite also occur in the rock. These pigeonite grains were often seen to have a narrow mantle of colourless carbonate which is probably of secondary origin.

The augites in the First Phase gabbros were found to be pale pink-brown varieties lying in a narrow range of compositions. The most magnesian type was found as euhedral phenocrysts in the lower marginal dolerite of the Hólar-Skessusaeti intrusion and these crystals have a composition of $Ca_{40}Mg_{40.5}Fe_{19.5}$ (No. 3) which is slightly more iron-rich than the augite in the eucrite. No exsolution lamellae were seen in these augites but a number of crystals were found to contain large numbers of minute ore particles arranged in narrow concentric zones parallel to the crystal margins. Pigeonite was not found in this rock, but small optically negative ortho-pyroxene crystals of pale green colour were found as independent grains in the dominantly augite-plagioclase groundmass, and these may represent original pigeonite inverted to orthopyroxene.

The Urdarfell gabbro contains pale pink-brown augite in large anhedral crystals showing some twinning parallel to (100); the composition of this pyroxene was determined as Ca_{40} $Mg_{39}Fe_{21}$ (No. 5) and no distinct exsolution lamellae were found in these augites. A few small rods of opaque material, probably ore, were seen to lie parallel to the (001) and (110) cleavages in these pyroxene crystals. No pigeonite was found in this rock. Many of the augite grains in this gabbro were found to be rimmed by pale green uralitic amphibole of similar type to that reported from the augites of the Vesturhorn (Cargill et. al., 1928.) and Hornafjördur gabbro intrusions (Annels, 1967).

The augite in the Steinsvad gabbro was found to be of similar type to that of the Urdarfell gabbro, with a composition of $Ca_{39.5}Mg_{38.5}Fe_{22}$ (No. 7) and a few faint striations parallel to (001) which may be lamellae of exsolved pigeonite were seen in these pyroxene crystals.

The compositional range of the augites in these First Phase gabbros (Nos. 3,5 and 7) is very similar to that of the augites of the LZb rocks of the Skaergaard intrusion which have a composition near $Ca_{38}Mg_{41}Fe_{21}$ and these augites crystallized together with An_{55-60} plagioclase as did those in the Vididalsfjall rocks (see Fig. 51) (Wager and Brown, 1968).

The compositions obtained for the Vididalsfjall gabbro augites reveal that they are similar types to those described from the Thingmúli basic lavas by Carmichael (1967a, Fig. 4, nos. 4 to 8); the Hornafjördur gabbros described by Annels (1967) bear augites of composition $Ca_{37.5}Mg_{34-36}Fe_{23-28}$, and these are rather more iron-rich than the augites from the Vididalsfjall First Phase gabbros.

2. Intermediate Rocks

The augites in the Urdarfell diorite and the basic granophyre hybrid (H_I) rocks were found to have very similar compositions, the diorite augites having a composition of $Ca_{40}Mg_{37}Fe_{23}$ (No. 10) and this lies close to the composition of the gabbro augites (Nos. 3, 5 and 7). The diorite augites show subhedral prismatic form with elongation parallel to the 'c' axis and were often seen to be twinned parallel to (100); the augites in the marginal and main facies showed the same general morphological characteristics, the augites in the marginal facies being smaller in size than those in the main facies. The diorite augites were seen to show a few thin exsolution lamellae parallel to (001) and some grains were found to be clouded by numerous minute ore particles or smaller numbers of ore blebs arranged in graphic texture. Some of the augite in the diorite was seen to be intergrown with the labradorite-andesine plagioclase in graphic texture and this is taken to indicate that the two minerals crystallised simultaneously.

Many of the augite grains in the diorite showed evidence of slight deformation and fracturing, some crystals showing distinct bending (see Plate 71a); this may be due to compaction or other mechanical stresses which operated during consolidation of the diorite, but may be due to actual transport of cumulus crystals of augite. The similarity of the compositions of these augite crystals and those of the gabbro augites is taken to suggest that the diorite augites were precipitated from a gabbroic liquid.

The augite in the basic granophyre (H_I) hybrid rock was found to have a composition of $Ca_{40.5}Mg_{39}Fe_{20.5}$ (No. 4) which coincides with the compositional range found in the gabbro augites. These H_I augites are pale pink-brown types like those in the diorite and gabbros and were found to bear very thin exsolution lamellae of pigeonite parallel to (001); some crystals contain minute ore particles like those in the diorite augites. No zoning was seen in these H_I augites, and the crystals are rimmed by green and brown clinoamphibole in similar fashion to the augites in the hybrid rocks of the Cairnsmore of Carsphairn complex (Deer, 1935).

The most striking feature of the H_I augites is their extreme elongation parallel to the 'c'-axis; the crystals have subhedral acicular habit and reach lengths of up to 6 mm with a length to breadth ratio of up to 8:1. Similar elongated pyroxene crystals have been found in the intermediate hybrid rocks of the Setberg area, Snaefellsnes (Sigurdsson, 1966a, p. 84-85), the Vesturhorn intrusions (J. Roobol, pers. comm., 1967) and Mull and Ardnamurchan (Bailey et al., 1924; Richey et al., 1930); the H_I augites appear particularly similar to elongated types described from the Gaodhail augite-diorite of Mull (Bailey et al., op. cit., p. 218), and the Mull rock as a whole is very similar to the H_I hybrid rock. The augite grains in the Gaodhail rock are rimmed with greenish-brown hornblende, and this mineral is characteristically developed as rims to augite crystals in the hybrid rocks of Mull (Bailey et al., op. cit.) where it is interpreted as having formed by reaction of augite with admixed acid material; a similar interpretation has been advanced by Deer (op. cit.) for the origin of the amphibole rims to the augites in the dioritic-gabbroic rocks of the Cairnsmore of Carsphairn complex.

The amphibole rims to the H_I augites are felt to be the result of reaction or corrosion caused by the acid material in similar fashion to the examples cited above; the evidence of disequilibrium, together with the evidence of fracturing and the compositional similarity of the augites to the First Phase gabbro augites, is believed to indicate that the H_I augites are xenocrysts which were precipitated in a gabbroic liquid. Similar corroded augite xenocrysts have been found in the more acid hybrid rocks of the Austurhorn intrusion by Blake (1966).

Evidence of a different type of reaction was found in the augites of the diorite walls to fine-grained hybrid (H_F) veins; at these contacts the diorite augites were seen to show a narrow optically continuous zone of pale green clinopyroxene, and this suggests that reaction with exchange of iron and magnesium took place to form a ferroaugitic pyroxene.

3. Acid Rocks

The clinopyroxenes in the fine-grained acid minor intrusions of the Vididalur-Vatnsdalur area were found to be iron-rich types of ferroaugite composition; these augites were seen as scattered phenocrysts in most of the rocks examined and were not found in the groundmasses of any of the First Phase rocks. No exsolution textures were found in any of the pyroxene phenocrysts in these acid rocks, and many were seen to enclose early-precipitated ore phenocrysts.

The Breidabólsstadur pitchstone was found to contain rare prismatic phenocryst of a very pale green to colourless ferroaugite of composition $Ca_{38}Mg_{24}Fe_{38}$ (No. 13); the curves of Carmichael (1960b) indicate a lower iron content than this value (see Table 11) and the phenocrysts are similar in composition to the ferroaugites of the Thingmúli andesites 14, 16 and 17 determined by Carmichael (1967a, Fig. 4, p. 1825.) This composition is surprising in view of the high silica content of the rock (71.5 per cent SiO_2 see Table 19) which is about 9 per cent higher than the most silicic andesite analysed by Carmichael (1964, Table 4, no. 17); no marked resorption or corrosion which might indicate chemical disequilibrium was seen in the Breidabólsstadur ferroaugites.

Phenocrysts of ferroaugite of composition $Ca_{39.5}Mg_{21.5}Fe_{39}$ were found in the 50-degree sheet south of Raudkollur (No. 14); these crystals are pale green, and faintly pleochroic, and their composition lies between the mean compositions obtained for the andesite and rhyolite of Thingmúli (Carmichael, 1967a, Table 3, nos. 17a and 18a). The 50-degree sheet ferroaugites were not found to show marked evidence of resorption, and one grain was seen to have a core of pale pink clinopyroxene which is taken to be of more magnesian character than its pale green rim.

Carmichael (1963a) has described the occurrence of magnesian pyroxene phenocrysts in rhyolitic pitchstones from eastern Iceland, and he cites a composition of $Ca_{38.3}Mg_{36.6}Fe_{25.1}$ for a chemically analysed example from Reydarfjördur; the examples described by Carmichael were not found to show marked evidence of zoning or dissolution which "suggests that they are to be accepted as being in equilibrium with their enclosing liquids" (Carmichael, 1963a, p. 395). Carmichael (op. cit.) notes that the titano-magnetite phenocrysts in the acid pitchstones are of early precipitation as they are enclosed by the pyroxene phenocrysts, and shows that the iron-ratios of these ore phenocrysts are higher than those of their enclosing pitchstones or residual glasses; this evidence indicates that the early precipitation of even a small amount of magnetite will impoverish the acid liquid in iron so that the pyroxene components in the liquids will become increasingly magnesian as magnetite continues to crystallize" (Carmichael, op. cit., p. 398).

The textural and compositional evidence of the Vididalur-Vatnsdalur pitchstones invites a similar interpretation, as the ore phenocrysts in these rocks are of early precipitation, being frequently enclosed by the pyroxene phenocrysts, and Carmichael's interpretation would explain the apparently too magnesian composition of the augites in the Breidabólsstadur and 50-degree sheet pitchstones.

The Dalsá-Urdarfell felsite contains scattered prismatic phenocrysts of pale green faintly pleochroic clinopyroxene with $2H_{\gamma} = 55.6-59.6^{o}$ (average 57.0°) which indicates a hedenbergitic type when this value is compared with either the Hess-Muir or Carmichael determinative curves; similar optic axial angle values have been reported from green hedenbergitic pyroxenes of the acid cone-sheets of the Setberg area by Sigurdsson (1966a), who points to the similarities between the pyroxenes in these rocks and those of the granophyres of Meall Dearg, Skye (Anwar, 1955) and the Skaergaard intrusion (Wager and Deer, 1939; Wager and Brown, 1968). Similar pyroxenes have also been found in the Tertiary fayalite-hedenbergite porphyries of Ubekendt Ejland, West Greenland (Drever 1958).

Crystals of clinopyroxene were found to be rare in the acid hybrids and granophyres of the First Phase. A few small ragged grains of pale green pyroxene with $\beta = 1.702$ were found in the granitic hybrid rock (H_G) and these grains were often seen to be pseudomorphed by amphibole and chlorite; no grains were found in suitable orientations for the direct determination of $2H\gamma$. Comparison of the refractive index value with the determinative curves, however, reveals that the clinopyroxene of the H_G rock would have a composition more typical of a diorite or an iron-rich gabbro; a value of $\beta = 1.702$ on the Hess-Muir diagram would represent an approximate composition of $(Ca\ Mg)_{72-79}$ Fe_{21-28} for the part of the field between the Ca_{50} line and the Thingmúli clinopyroxene trend (Carmichael, 1967a). It seems possible that the H_G pyroxene represents a xenocryst which has reacted with the enclosing acid material in the same fashion as the augites in the diorite walls of H_F veins, and the frequent replacement of the H_G pyroxene by amphibole is taken to indicate its disequilibrium.

Pyroxenes were found to be almost completely absent from the pale MU granophyre but scattered small bright green chloritic pseudomorphs after subhedral pyroxene phenocrysts were found in the fine-grained spherulitic parts of the granophyre; the groundmass of this rock was also found to contain small acicular pseudomorphs after pyroxene of similar colour to the larger crystals.

Fresh phenocrysts of faintly pleochroic pale green clinopyroxene were found in the small patches of pyroxene granophyre in the MU intrusion and these were seen to be moulded on to the andesine-oligoclase and olivine crystals in the rock and to enclose ore phenocrysts. The pyroxene grains show some colour zoning, with pale green cores passing outwards into bright grass-green rims; the cores of the crystals are of a slightly more intense green colour than the ferroaugites in the other acid rocks. This pyroxene was found to have $2V_{\alpha} = 79\text{-}99^{\circ} \pm 2^{\circ}$ and $\beta = 1.738 \pm 0.005$ which indicates that it is an aegirine-augite of composition $Fe^{III}_{0.28-0.52}$ (Deer, Howie and Zussman, 1965, Vol. 2, Fig. 28).

Green sodic aegirine-augite or aegirine pyroxenes have been reported from other granophyre intrusions in eastern Iceland, and their optical properties are given in Table 12.

Table 12

Optical Properties of Sodic Pyroxenes from Icelandic Granophyres

Slaufrudal, (Beswick, 1965)	$2V_{\alpha} = 70^{\circ}$	-
Austurhorn, (Blake, 1966)	$2V_{\alpha} = 66\text{-}82^{\circ}$	$\beta = 1.740 \pm 0.005$
Ketillaugarfjall, (Annels, 1967)	$2V_{\alpha} = 120^{\circ}$	-

Aegirine-augite has also been found in acid rocks in Snaefellsnes, western Iceland, notably in an intrusive pitchstone from Drápuhlídarfjall and in an acid lava near Snaefellsjökull (Peacock, 1924); the mineral is also known to occur in the acid lava of Dómadalshraun, mid-southern Iceland (Peacock, op. cit.)

Similar sodic pyroxenes are known to exist in some of the other North Atlantic Tertiary acid intrusions, notably Holy Island, Arran (Tyrrell, 1928), Rockall (Sabine, 1960) and Mull (Bailey et al., 1924, pp. 21, 334, 348).

(b) THE SECOND PHASE ROCKS

1. Basic Rocks

The clinopyroxenes in these rocks were found to be of broadly similar composition to those in corresponding rocks of the First Phase, but the compositions determined are slightly more iron-rich than those of the augites in the earlier-formed basic intrusive rocks.

The Skessusaeti summit eucrite was found to bear a pale pink-brown interstitial augite of composition $Ca_{41}Mg_{40}Fe_{19}$ (No. 2) and this is noticeably more iron-rich than the augite of the Hólar-Skessusaeti eucrite (No. 1); no exsolution textures were found in the augites of the summit eucrite but a few grains were seen to have rims of near-uniaxial pigeonitic pyroxene, in similar fashion to the augites of the First Phase eucrites. Some of the augites in these Second Phase rocks are twinned parallel to (100).

The Second Phase Type 1 and 2 cone-sheet material contains a pale pink-brown groundmass augite of composition

$Ca_{38-39.5}Mg_{36-39}Fe_{21.5-26}$ (Nos. 6, 9, 9a and 11) which is a markedly more iron-rich type than the groundmass pyroxene of the early set cone-sheets (Nos. 15 and 16); this composition is very similar to that of the augites in the Thingmúli olivine-tholeiites and tholeiites (Carmichael, 1967a, Table 3 and Fig. 4, nos. 2, 3 and 4), and also to that of the augite of the Hornafjördur gabbros (Annels, 1967, see p. 503, this work). The Vididalsfjall Second Phase augites were not found to show exsolution textures, but many of the groundmass crystals in the cone-sheets have rims of pigeonitic pyroxene, and this mineral was also seen to occur as occasional independent groundmass crystals. The most iron-rich pyroxene in the range of compositions determined was that of the Gálgagil plug, and the value obtained was $Ca_{38}Mg_{36}Fe_{26}$. (No. 11). The apparent lack of exsolution textures in the pigeonitic pyroxenes of these Second Phase minor intrusive rocks is felt to suggest that cooling of the magma was too rapid for exsolution to occur (Deer, Howie and Zussman, 1965, Vol. 2, p. 148); the rapid cooling of the Second Phase eucrite and cone-sheets is also evidenced by the presence in these rocks of high-temperature plagioclase.

The gabbro core of the Hnjúkur plug was found to bear interstitial augite of composition $Ca_{38}Mg_{38.5}Fe_{23.5}$ (No. 8) and this composition lies within the range found in the Second

Phase eucrite and tholeiite pyroxenes. A few thin exsolution lamellae were found in the augites and these are taken to indicate that the Hnjúkur gabbro underwent rather slower cooling than the other basic intrusions of the Second Phase due to its lower level environment. (see Map 1); the euhedral to subhedral form of the Hnjúkur augites may also be the result of fairly slow cooling, although the presence of high-temperature plagioclase in the rock indicates that such cooling occurred under essentially volcanic conditions.

2. Acid Rocks

The acid central part of the Gálgagil composite intrusion bears scattered phenocrysts of pale green clinopyroxene which were identified as ferroaugite of composition $Ca_{44}Mg_{22.5}Fe_{33.5}$ (No. 12) (or $Ca_{48}Mg_{24}Fe_{28}$ by the Carmichael (1960b) curves). This pyroxene thus has a high calcium content which places it in or near to the hedenbergite field (Deer, Howie and Zussman, 1965, Vol. 2, Fig. 4). No evidence of exsolution was found in these pyroxene phenocrysts, and the composition obtained is more calcic than that of any of the pyroxenes described by Carmichael from eastern Iceland (Carmichael, 1960b, 1967a.) The rims of these pyroxene crystals show a "spongy" texture, and Carmichael (1960b) suggests that similar spongy rims to ferroaugite phenocrysts from a glassy acid rock in eastern Iceland may be due to incipient recrystallization; the texture in the Gálgagil augites may be due to a similar process, and the phenomenon may also be due to reaction of the pyroxene with the acid residual liquid. The pyroxene crystals were frequently seen to enclose small early-precipitated ore phenocrysts which suggests that they were precipitated at a later stage in the crystallization of the rock; it is difficult to reconcile the high calcium content of the pyroxenes with their late stage of crystallization, and the fact that they contain ore phenocrysts makes it unlikely that they are xenocrysts derived from the basic margins of the Gálgagil intrusion. Xenocrysts of labradorite plagioclase of similar type to those seen in the basic margins do occur within the acid material and their presence is taken to indicate some mixing of the basic and acid material prior to emplacement of the intrusion. The origin of the calcic ferroaugite is not fully understood, but it is tentatively suggested that the acid liquid acquired some calcium from the basic tholeiitic marginal material during this mixing process after precipitation of ore and plagioclase and was thus enabled to precipitate a relatively calcium-rich pyroxene in the later stages of its cooling. This admixture of calcium at a fairly advanced stage of crystallization of the phenocryst phases may also be responsible for the presence in the rock of microphenocrysts of andesine half the size of the larger andesine phenocrysts but with very similar core compositions indicating an apparently extended period of precipitation of An_{34-30} plagioclase.

Pale green clinopyroxenes of apparently similar type to the phenocrysts also occur in the groundmass of the Gálgagil intrusion as small acicular crystals similar to those found in the craignurite types of the Hebridean Tertiary Province (Bailey et al., 1924, p. 225-228; Richey et al., 1930); these Gálgagil pyroxenes may show exceptional elongation in small patches (see Fig. 83) with length to breadth ratios up to 50:1 and this is believed to be due to crystallization in volatile-rich pockets within the groundmass. A similar habit is known to exist in augites within the acid residual patches of the Permo-Carboniferous quartz-dolerites of the Midland Valley of Scotland (Walker and Irving, 1928); the acicular augites from all three localities cited are strung with small granules of opaque ore.

The phenocryst and groundmass clinopyroxenes in the Krossdalur intrusion are of similar appearance to those in the Gálgagil intrusion; their composition was not determined, but they are believed to be ferroaugite-hedenbergite types by analogy with these types.

4-5 ORTHOPYROXENES

Orthopyroxenes were not found to be abundant in the Vididalur-Vatnsdalur intrusive rocks, and the crystals of this mineral found in the basic rocks usually proved to be inverted pigeonite; such pyroxenes have already been mentioned in the section on clinopyroxenes (p.497 and Fig. 89).

Fresh orthopyroxene crystals were found in only one rock in the area studied, and these occur as often euhedral stumpy prisms up to 0.5 mm in length in the glassy pitchstone margin of the Breidabólsstadur acid intrusion; this orthopyroxene was seen to show a faint pink to grey pleochroism (X very pale pink-brown, Y paler pink-brown, Z very pale grey) and its optical properties were found to be $\beta = 1.705 \pm 0.002$, $2V_{\alpha} \sim 60^{o}$. These values indicate a composition of about Fs_{35} (Deer, Howie and Zussman, 1965, Vol. 2.) which is more magnesian than any of the orthopyroxene phenocrysts described from Icelandic acid rocks by Carmichael (1960b, 1963a, 1967a and b); this composition is however similar to that of the orthopyroxene phenocrysts from the Sgurr of Eigg pitchstone (Fs_{33}) and the Glen Shurig pitchstone dyke, Arran (Fs_{32-37}) investigated by Carmichael (1960b), and the chemical analysis of this last rock shows marked similarity to that of the Breidabolsstadur pitchstone (see Table A , Appendix, Part 2).

The compositions of the two pyroxene phenocryst types found in these rocks are given below in Table 13, together with those of the chemically analysed augite and hypersthene phenocrysts from the Holmanes rhyolite of the Reydarfjördur area, eastern Iceland (Carmichael, 1963a, Table 1).

Table 13.

	Clinopyroxene	Orthopyroxene
Sgurr of Eigg	$Ca_{40.1}Mg_{42.5}Fe_{17.3}$	$Ca_{4.4}Mg_{62.6}Fe_{33.0}$
Glen Shurig	$Ca_{42}\ Mg_{16}\ Fe_{42}$	Fs_{32-37}
Breidabólsstadur	$Ca_{38}\ Mg_{24}\ Fe_{38}$	Fs_{35}
Holmanes	$Ca_{38.3}\ Mg_{36.6}\ Fe_{25.1}$	$Ca_{3.4}\ Mg_{49.5}\ Fe_{47.1}$

The Sgurr of Eigg pyroxenes are believed to be in equilibrium with one another, but the Glen Shurig pyroxenes are not thought to be in equilibrium as the orthopyroxene forms irregular cores to mantles of ferroaugite (Carmichael, 1960b, 1967b).

The Breidabólsstadur orthopyroxenes were not seen to form cores to the ferroaugites in the rock, nor were they found to show any corroded margins indicative of disequilibrium; a few grains however were seen to show narrow optically continuous rims of slightly darker brown material which may represent zoning towards more iron-rich orthopyroxene, but the composition of these rims was not determined. The orthopyroxenes appear to have been among the first phenocrysts to form as they are moulded on to the ore phenocrysts in the rock and are themselves partly enclosed by phenocrysts of andesine (An_{41}) which are presumably of later crystallization.

It is concluded that these orthopyroxene phenocrysts began their crystallization in a more basic liquid than that represented by the Breidabólsstadur pitchstone and continued to crystallize within the more acid liquid to form narrow rims of more iron-rich material; part of the early crystallization of the pyroxene may have taken place under the relatively magnesium-rich conditions resulting from the early precipitation of ore. It seems possible that these conditions were then reversed towards progressive iron-enrichment by the later more dominant precipitation of ferromagnesian silicates from the liquid (Carmichael 1963a, 1967b).

4-5 OLIVINE

(a) THE FIRST PHASE ROCKS. 1. Basic Rocks

No fresh olivines were found in these rocks, and all the rocks examined bear greenish or brownish pseudomorphs after olivine; this feature is believed to be due to the combined effect of contemporaneous deuteric and later regional hydrothermal alteration.

The olivine grains are commonly pseudomorphed by a pale green finely fibrous mineral or low birefringence, and this has been called bowlingite for the purposes of the present study; bowlingite is known to be particularly common as an alteration product of olivine in shallow-level basic intrusions (Deer, Howie and Zussman, 1965, Vol.1,p.18) and it is widely accepted as being a product of deuteric alteration. The composition of bowlingite has been studied in detail by Wilshire (1958) and will not be reconsidered here.

The olivine pseudomorphs in the Hólar-Skessusaeti eucrite were found to show subhedral slightly elongated forms from 2-7 mm in length, the larger sizes being apparently more abundant in the main facies of the eucrite than in the chilled marginal rock; these olivines were sometimes seen to be associated with the large bytownite crystals in the rock and their presence in the chilled marginal rock is taken to indicate that they are early-formed cumulus crystals precipitated some time before emplacement of the eucrite. In parts of the eucrite the rims of these olivine grains were seen to enclose the tips of the small plagioclases in the rock, indicating that olivine crystallization continued parallel to the crystallization of the groundmass. Small independent olivine grains in the interstitial material of the Borgarvirki eucrite were found to be enclosed by augite grains and also to "share" small plagioclase grains with augite crystals of simultaneous crystallization (p .. 317 ..). It seems possible that these olivine grains are zoned, by analogy with the olivines in the Second Phase basic rocks in which the cores of the most magnesian olivines were found to have a composition of Fa_{20} the rim composition of these olivines is not known, but may be near Fa_{40}, by analogy with the olivine precipitated in company with An_{60} plagioclase from the Skaergaard liquids (Wager and Brown, 1968).

No olivine was found in the early set cone-sheets apart from that forming part of the eucritic inclusions already described (p 324 ..); these olivines are pseudomorphed by green bowlingite and are essentially similar in character to the olivines of the eucrite intrusions, being of early precipitation and often poikilitically enclosed by augite crystals.

<u>Table 14</u>

OPTICAL PROPERTIES AND COMPOSITIONS OF OLIVINES FROM THE VIDIDALUR-VATNSDALUR ROCKS

Rock type	Number on Fig. 90.	Specimen number	$2H_\alpha$ range	Average $2H_\alpha$	$2V_\alpha$	β	Composition (mol.% Fa) range	average
Eucrite	2	Vi 95	-	-	-	1.702	n.d.	24.5
Olivine-tholeiite	9	Vi 320	-	-	-	1.709-1.781	28-62	49.0
Eucrite	9a	Vi 85	-	-	-	1.697	n.d.	22.5
Olivine-tholeiite	11	Vi 76	-	-	-	1.694-1.705	20.5-26	23.3
Acid pitchstone	14	Vi 178	57.3-59.0	58.2	51.8	1.835	88-93	90.5

2. Intermediate Rocks.

Olivine was found in the small schlieren within the main facies of the Urdarfell diorite as pseudomorphs composed of greenish to brownish fibrous material; the form of the original olivine crystals is difficult to discern and the pseudomorphs form areas of ragged outline up to about 4 mm across which are believed to be of a relatively late stage of crystallization as they enclose small crystals of clinopyroxene and zoned feldspar (see Fig. 73). The original composition of these olivines may have been very similar to that of the olivines in UZ the Skaergaard UZ rocks (Wager and Brown, 1968); these Skaergaard olivines, precipitating together with An_{45-30} plagioclase, were found to have a composition in the range Fa_{60-100}.

3. Acid Rocks

Olivine was found as fresh phenocrysts of rounded form up to about 1.2 mm in size in the 50-degree sheet; these grains were found to enclose small crystals of andesine and ore and to have equant to amoeboid habit (see Fig. 64). The composition of these olivines was determined as $Fa_{90.5}$, this being the average of the values obtained by $2V_{\alpha}$ (Fa_{93}) and β measurements (Fa_{88}) (see Table 14 and Fig. 90, No. 14.) This value lies in the range of values obtained for olivines from the fine-grained acid rocks of eastern Iceland by Hawkes (1924),

Table 15

OCCURRENCES OF FAYALITE-BEARING GRANOPHYRIC ROCKS FROM THE NORTH ATLANTIC TERTIARY IGNEOUS PROVINCE.

With sodic clinopyroxene :

Beinn a' Ghraig granophyre	Mull	Hawkes (1925)
Austurhorn granophyre	Eastern Iceland	Blake (1966)

With hedenbergitic clinopyroxene :

Meall Dearg granophyre	Skye	Anwar (1955)
Beinn Dearg Mhor epigranite	Skye	Wager et al.(1965)
Loch Ainort "	"	"
Marsco "	"	"
Meall Buidhe "	"	"
Brödretoppen granophyre	Eastern Greenland	Wager and Deer (1939)
Ubekendt Ejland acid porphyry	Western Greenland	Drever (1958)
Austurhorn granophyre	Eastern Iceland	Blake (1966)

Cargill et al. (1928) and Carmichael (1960b, Table 4, Nos. 6B, 8B, 9B). The compositions of the olivines chemically analysed by Carmichael (op. cit.) lie in the range $Fa_{86.7-89.3}$.

A few small pseudomorphs after olivine were found in phenocryst clusters in the pyroxene-granophyre facies of the MU granophyre, and these are composed of finely fibrous yellow-brown material with low birefringence; these pseudomorphs after olivine were sometimes seen to show euhedral near-equant form with well-developed (021) faces, and are felt to be of relatively early crystallization as they enclose small ore phenocrysts and are themselves partly enclosed by phenocrysts of aegirine-augite and oligoclase. It seems likely that these olivines were originally highly fayalitic, as fayalite has been found in similar granophyres in the Austurhorn intrusion (Blake, 1966) and in the Beinn a' Ghraig granophyre of Mull (Hawkes, 1925); the MU granophyre shows many features in common with these two granophyres, notably the development of aegirine-augite. Fayalitic olivine has been found in other granophyres of the North Atlantic Tertiary Province, and these occurrences are listed in Table 15.

(b) THE SECOND PHASE ROCKS

Olivine was found to be present only in the basic rocks of the Second Phase, and the range of compositions encountered as $Fa_{20.5-62}$. The most magnesian compositions were found in the cores of phenocrysts in the eucrites and late set cone-sheets, and these crystals were found to have subhedral forms up to 2.0 x 1.0 mm in size (see Figs. 80, 81b); the crystals are mostly fresh, but some green or orange-brown fibrous material is commonly developed along the irregular cleavage cracks of the olivines.

The cores of the large olivine phenocrysts in the eucrite and late set cone-sheets were often found to pass with optical continuity into rims which enclose the tips of groundmass plagioclase laths (see Fig. 80) in similar fashion to the olivine phenocrysts of the First Phase eucrites; this texture indicates that crystallization of olivine continued during the period of groundmass crystallization, and an extended period of olivine precipitation is indicated by the presence of the groundmass of small olivine crystals of more iron-rich composition than the phenocryst cores. These small olivine crystals are interpreted as microphenocrysts and were found to have core compositions in the range Fa_{28-62} in one of the olivine-tholeiite sheets and the compositions of six crystals (derived from β refractive index measurements) were found to be Fa_{28}, Fa_{38}, Fa_{44}, Fa_{59}, Fa_{61}, Fa_{62}. The upper limit of this range lies near to the composition of the larger phenocrysts, and it seems likely that the compositions of the phenocryst rims and the groundmass olivines lie in the same range; groundmass olivines in the Gálgagil plug olivine-tholeiite were found to have compositions in the range $Fa_{20.5-26}$ (Table 14 and Fig. 90, No. 11). The largest compositional break in the series of olivines determined for these late-set tholeiites lies between Fa_{44} and Fa_{59}, and this shows part coincidence with the distinct periods of non-crystallization of olivine found in the highly fractionated Skaergaard and Thingmúli rocks; the gap in the Skaergaard olivine compositions is between about Fa_{48} and Fa_{64} and the corresponding gap in the Thingmúli series is from about Fa_{52} to Fa_{63} (Wager and Brown, 1968; Carmichael, 1967a, Fig. 4). This non-crystallization period of olivine in fractionating liquids was predicted by Bowen and Schairer (1935) from experimental work in the system MgO - FeO - SiO_2, and it seems possible that the apparent gap in olivine compositions within the Second Phase olivine-tholeiites may be explained in the same way.

4-6 AMPHIBOLE

Amphiboles were found only within the First Phase rocks, where they are largely restricted to the Urdarfell hybrid rocks and the MU granophyre.

The clinopyroxene crystals in the Urdarfell diorite and the H_F and H_I rocks were found to bear rims of pale brown clinoamphibole with $Z \wedge c = 25^{\circ}$ and a variable pleochroism scheme :

X	straw	X straw
Y	pale green-brown	Y pale brown
Z	green-brown	Z medium brown

Absorption : $X < Y < Z$

This amphibole was found to have $2V_{\alpha} = 67^{\circ}$ (optic axial plane parallel to (010),) and $\beta = 1.659 \pm 0.002$ suggesting that it is a hornblende. (Deer, Howie and Zussman, 1965, Vol. 2.)

In many of the fine-grained (H_F) hybrid rocks the elongated clinopyroxene grains were seen to be in various stages of replacement by brown amphibole, ranging from grains with narrow cores of near-colourless augite and homoaxial rims of amphibole to complete elongated grains of amphibole. The small scattered inclusions of fine-grained basic material in the hybrid rocks were also seen to bear brown or green-brown amphibole and this is taken to be due to replacement of the original pyroxene in the rock. No apparent regularity in the distribution of brown and green-brown amphibole was found in these hybrid rocks.

The clinopyroxenes in the coarser-grained H_I hybrid rocks have rims of brown or green-brown amphibole, the two amphibole types often occurring in the same rock and being of the same type as those seen in the H_F rocks. A few scattered grains of green-brown amphibole were also found in the Type 2 acid veins associated with the Urdarfell hybrid rocks.

The replacement of clinopyroxene by amphibole in the Urdarfell rocks is a similar phenomenon to that observed in the hybrid augite-diorites of Gaodhail, Mull (Bailey et al. 1924), Camphouse, Ardnamurchan (Richey et al., 1930) and the basic-acid hybrid rocks of the Cairnsmore of Carsphairn complex (Deer, 1935.) and Barnavave (Nockolds, 1938). Other examples of such replacement in Icelandic hybrids have been described from the Vesturhorn intrusion (Cargill et al., 1928) and the Austurhorn intrusion (Blake, 1966).

Some development of a very pale green optically negative amphibole with moderate to large $2V_\alpha$ (optic axial plane parallel to (010)) was seen at the margins of the augite grains in the Urdarfell gabbro, especially in the region of small hybrid inclusions in the gabbro; this amphibole was found to have $Z \wedge c = 16^{\circ}$, and the pleochroism scheme :

X straw

Y very pale yellow-green   Absorption $X < Y < Z$

Z pale yellow-green

This amphibole shows similar properties to actinolite and is similar to the type referred to as "uralite" (Deer, Howie and Zussman, 1965, Vol. 2, p. 260). It seems likely that the mineral formed by the action of volatiles on the pyroxenes in the rock; these volatiles may have originated either from the unconsolidated hybrid inclusions or the final portions of the gabbro liquid. Similar alteration of pyroxene in gabbros has been reported from the Vesturhorn intrusion (Cargill et al., 1928) and the Hornafjördur area (Annels, 1967).

The granitic H_G hybrid rock was found to contain scattered ragged blades of a bright green amphibole which occurs either as independent crystals or as rims to the green clino-pyroxene in the rock; this amphibole was found to be optically negative with $2V_{\alpha}$ of about 60° (optic axial plane parallel to (010)) and to have $X \wedge c = 49\text{-}56^{\circ}$; extinction positions were sometimes difficult to judge due to the strong absorption of the mineral.

The amphibole has low birefringence and its pleochroism scheme was found to be :

X pale brown-green
Y medium olive-green Absorption: $X < Y > Z$
Z bright grass-green to blue-green

The association of this mineral with sodic pyroxene and its general optical properties suggest that it may be a sodic amphibole (Deer, Howie and Zussman, 1965, Vol. 2.). Amphibole of similar type was found in a few cavities within the rock as small needles or blades up to 0.5 mm in length with $Z \wedge c$ about 24°; these crystals are often seen to be set in interstitial areas of pale carbonate and are thus thought to be of late crystallization. Fibrous green or blue-green amphibole crystals enclosed by calcite have been found in the hybrid rocks of Barnavave (Nockolds, 1938, Fig. 2 and pp. 472-474.) and similar amphibole was seen to replace part of the green pyroxene in these rocks.

A few small ragged grains of similar bright green amphibole were found in the Type 2 acid veins on Urdarfell. A grass-green amphibole has been found in the pyroxene-granophyres of the Slaufrudal stock (Beswick, 1965); these Slaufrudal rocks contain green sodic pyroxene.

The pyroxene-granophyre facies of the MU granophyre on Urdarfell was found to bear scattered ragged grains of a dark blue amphibole of late crystallization interstitial to the matrix feldspars of the rock; this mineral shows intense pleochroism according to the scheme :

X brownish grey to green-grey

Y blue-grey   Absorption $X < Y < Z$

Z dark green-blue

The very strong absorption colours of this mineral and the small size of the crystals make exact determination of the optical orientation difficult, but the amphibole has a moderately large negative 2V with the optic axial plane perpendicular to (010) and $Z \wedge c = 23\text{-}26^\circ$.). The mineral was seen to show typical amphibole cleavages intersecting at about 60° and 120° in basal sections and is felt to be a sodic amphibole related to arfvedsonite on the basis of the brown colours seen in its pleochroism scheme (Deer, Howie and Zussman, 1965, Vol. 2.) Small quantities of amphibole with optical properties suggestive of arfvedsonite have been reported from the Ketillaugarfjall granophyre of the Hornafjördur area (Annels, 1967) where the amphibole is intimately associated with aegirine-augite.

The only other amphibole found in the Vididalur-Vatnsdalur rocks was seen as small euhedral prismatic phenocrysts up to 0.5 x 0.2 mm in size in the Breidabólsstadur pitchstone. These phenocrysts were found to be independent of all other phenocrysts in the rock and to have $Z \wedge c = 27^{o}$ with the pleochroism scheme :

X pale brown

Y medium brown Absorption : X < Y < Z

Z medium purplish-brown

The scarcity of amphibole phenocrysts in the known glassy acid rocks of Iceland has already been mentioned (p. 363).

A number of amphibole phenocrysts from glassy acid volcanic rocks have been analysed using electron microprobe techniques and most of these were found to be titanium-rich hornblendes (Carmichael, 1967b); the amphiboles in the Breidabólsstadur rock may be of a similar type.

4-7 ORE MINERALS

No detailed study of these minerals was made, but their textures are interesting in that they show similarity to those of the Skaergaard and Thingmúli ore minerals.

1. Basic Rocks

The main period of ore crystallization in these rocks appears to have been during the later part of their cooling history, as the majority of the opaque ore grains were usually seen to be moulded on to the latest-formed pyroxene and plagioclase crystals in the eucrites, cone-sheets and gabbros, often forming poikilitic intergrowths with these plagioclases. Examination of the chilled margins of the Hólar-Skessuaeti eucrite and those of cone-sheets of early and late sets revealed the presence of small opaque ore phenocrysts of two types. Phenocrysts of the first type were seen to have euhedral acicular form and to be independent of intergrowth with other minerals. Phenocrysts of the second type were found to be more or less equant in form and to have irregular margins which were intergrown with the groundmass feldspar and pyroxene crystals and were sometimes seen to enclose apatite crystals. These two types are believed to be ilmenite and magnetite (sensu lato) as they show similar form to the examples of these minerals studied in reflected light by Vincent and Phillips (1954) and Wright (1961). The acicular ilmenite crystals were found to be particularly common in the fine-grained groundmasses of the early and late set cone-sheets and were often found to form intersecting "gridiron" patterns near the margins of these sheets. Similar minute ore needles were often found in the glassy residua filling the final mesh gaps in the late set Type 1 and 3 cone-sheets. Single acicular ore crystals were often seen to be partly or wholly enclosed by silicate minerals in the same fashion as those described by Wright (op. cit.). The acicular crystal types were not found to be so abundant in the coarser-grained parts of the eucrites, cone-sheets and gabbros, and the ore in these rocks was found to occur mainly as large ragged anhedral grains occupying the interstices of the plagioclase-pyroxene fabrics (see Fig. 54). A similar occurrence of acicular and ragged ore grains in the tholeiitic basic lavas of Thingmúli has been described by Carmichael (1964, 1967a) who identified the two respective types as ilmenite and magnetite.

The ore grains in the gabbros tend towards equant forms which may show slightly skeletal centres, and it is possible that the large ore grains in these rocks and the eucrites are composite aggregates of ilmenite and magnetite by analogy with the types identified in the Skaergaard gabbros by Wright (1961).

A few near-equant ore grains in the Hnjúkur gabbro were found to be partly enclosed by the augites in the rock and these may represent early-precipitated ore phenocrysts of similar type to those found in the fine-grained margins of some of the early and late set cone-sheets (see Fig. 58).

2. Intermediate Rocks

The ore phenocrysts in the marginal facies of the diorite were often seen to be partly enclosed by pyroxene grains, and other ore grains within the main facies of the diorite were seen to have ragged more or less equant forms moulded on to pyroxene and feldspar crystals; this evidence is felt to suggest that the period of ore precipitation overlapped that of pyroxene, but does not necessarily indicate that ore precipitation was continuous over this period. Some acicular ore crystals were found in the marginal facies of the diorite, and "graphic" patches of small regularly-arranged ore blebs were found in the pyroxenes of the main facies of the diorite; these graphic patches were sometimes seen to fringe large more or less equant ore grains partly enclosed by the pyroxene and may represent simultaneous crystallization of ore and pyroxene.

The ore grains in the H_I hybrid rocks were often seen to be partly enclosed by the acicular pyroxene crystals in similar fashion to those in the diorite (see Fig. 76); the H_I rock was also seen to contain numerous large subhedral skeletal ore crystals having the appearance of parallel intergrowths of acicular crystals.

Small euhedral acicular ore crystals about 0.5 mm in length were commonly found scattered through the granitic glomerogranular patches in these H_I rocks.

Only a few ore crystals in the diorite and H_I rocks were found to be moulded on to the pyroxene and plagioclase crystals and this is taken to indicate that the main phase of ore precipitation took place before mixing of the diorite and acid material.

3. Acid Rocks

The ore phenocrysts in the fine-grained acid minor intrusions were found to be mostly equant polyhedral grains, although a few grains with oblong sections were seen in these rocks. These ore grains were invariably seen to be enclosed by the olivine and pyroxene phenocrysts and were often seen to be enclosed partly or wholly by plagioclase phenocrysts; this is taken to indicate that the ore phenocrysts were precipitated early in the cooling history of the acid rocks, a relationship similar to that observed in the acid minor intrusions of eastern Iceland (Carmichael, 1960b, 1963a, 1964, 1967 a and b).

On account of their apparent similarity to the ore phenocrysts of the examples cited, the ore phenocrysts are taken to be titanomagnetites.

Similar ore phenocrysts were found in the MU granophyre and the H_G rock, and these also appear to be of early crystallization on the same grounds as those in the fine grained acid rocks.

4-8 QUARTZ

Quartz was found in most of the rocks examined, commonly occurring in graphic intergrowth with alkali feldspar in the final mesh gaps of the eucrites, gabbros and cone-sheets (see Fig. 57b.)

The gaps in the fabric of the Skessusaeti summit eucrite and the Hnjúkur core gabbro were sometimes seen to bear paramorphs of quartz after platy tridymite; these paramorphs show greatly elongated sections with length to breadth ratio about 20:1 and were often found to consist of single quartz crystals which gave oblique extinction in similar fashion to the tridymite paramorphs described by Wager et al., (1953) and Skelhorn (1962). The presence of tridymite in the Vididalur-Vatnsdalur basic rocks is taken to suggest that these intrusions were emplaced at relatively high levels (Brown, 1963); the Skessusaeti summit eucrite is at an elevation of 939 m, in a position which lies at about 300 m below the present day top of the lava-pile.

Quartz was found to be abundant in the main facies of the diorite and in all the hybrid rocks, where it is associated with alkali feldspar in graphic intergrowths of variable fret size and as anhedral equant grains in glomerogranular aggregates (Hawkes, 1929; Beswick, 1965). These quartz grains in graphic intergrowth with feldspar are taken to be of α-quartz, as this form is held to be the characteristic type of such intergrowths (Kerr, 1959.)

The acid rocks were found to bear a greater number of quartz types than the basic and intermediate rocks; the groundmasses of the finer-grained rocks such as the Dalsá-Urdarfell and Raudkollur felsites were found to be patchwork fabrics of ragged interlocking quartz and alkali feldspar grains, and the quartz grains in some of these rocks were seen to have the platy form characteristic of paramorphs after tridymite (see Fig. 63).

Similar quartz paramorphs after tridymite have been described in Tertiary acid rocks from eastern Iceland by Hawkes (1916) and Walker, (1959) and also from Snaefellsnes, western Iceland, by Sigurdsson (1966a) p. 75); paramorphs after tridymite have also been found in a number of acid intrusions in the Hebridean area notably the Coire Uaigneich granophyre of Skye (Wager et al., 1953, Brown, 1963) and a craignurite cone-sheet in Mull (Skelhorn, 1962). These authors attribute the formation of tridymite in these instances to the crystallization of acid material at shallow depths of the order of 1000 m, and by analogy, the examples found in the Vididalsfjall rocks are felt to have formed at similar shallow depths (see p 339).

The granophyres studied contain abundant quartz and feldspar in graphic intergrowth (see Figs. 68 and 69) this relationship is typical of granophyres (Harker, 1962, p. 96) and has been observed in numerous types in the North Atlantic

Tertiary Province . In the Icelandic types, the graphic intergrowths commonly enclose plagioclase phenocrysts (Cargill et al., 1928; Carmichael, 1964; Beswick, 1965; Blake, 1966; Sigurdsson, 1966a; Annels, 1967) and this texture is due to the cooling under hypabyssal conditions of the final part of the acid magma (Carmichael, 1963b.). If the degree of cooling or loss of volatiles is relatively rapid, this final part of the acid magma may form spherulitic quartz-alkali feldspar rims to the plagioclase phenocrysts, as in some of the Slaufrudal granophyres (Beswick, 1965.); spherulites of this type have been found in the marginal facies of the MU granophyre (see Figs. 66 and 67).

Some of the Vididalur-Vatnsdalur holocrystalline acid rocks were found to bear scattered phenocrysts of quartz (see Figs. 65a and 66b); these phenocrysts were most clearly seen in the finer-grained, more rapidly cooled rocks such as the small felsitic intrusions in the Gálgagil vent zone, the Kornsá acid sheet, and the margins of the MU granophyre. All of the phenocrysts found showed square or hexagonal sections, and they are thus taken to be of bipyramidal form; this form is characteristic of high-temperature or β-quartz (Kerr, 1959.).

Euhedral bipyramidal quartz crystals with sharp outlines were seen at the centres of spherulites in the fine-grained feldsparphyric marginal facies of the MU granophyre (see Fig. 66b); these crystals showed few embayments which might indicate extensive resorption, and were found to be much smaller than the feldspar phenocrysts in the rock, with maximum lengths of about 0.2 mm. The small size of these quartz phenocrysts is felt to suggest that they were among the last phenocrysts to precipitate before the final rapid chilling of the MU liquid.

Similar quartz phenocrysts of slightly larger size (up to 1 mm, commonly 0.5 mm) were seen in the Kornsá and Gálgagil sheets and the Urdarfell Type 2 acid veins (p. 359); these crystals often showed skeletal forms which may be the result of corrosion and resorption (Deer, Howie and Zussman 1965 Vol. 4; see Fig. 65a this work).

The quartz phenocrysts examined were usually to be surrounded by a narrow mantle of very fine-grained quartz-feldspar intergrowth, and this mantle was sometimes seen to be continuous with the phenocryst, which suggests that the phenocryst rim crystallized at the same time as the groundmass.

Quartz phenocrysts are rare in the known acid rocks of Iceland, but some recently described occurrences are listed in Table 16.

Table 16

OCCURRENCES OF QUARTZ PHENOCRYSTS IN ICELANDIC ACID ROCKS

Eastern Iceland.		
Berufjördur	Basal pitchstone of rhyolite lava.	Carmichael, 1963b.
Fáskrúdsfjördur	Rhyolite of composite lava flow.	Gibson et al., 1966, p. 34.
"	Composite dyke.	Ibid., p. 46.
Western Iceland		
Setberg, Snaefellsnes.	Acid cone-sheet.	Sigurdsson, 1966a, p. 76.

The Setberg example has been interpreted as being of late-state growth (Sigurdsson, op. cit., p. 76.)

Carmichael (1963b, p. 110) has suggested that crystallization of a one-feldspar acid liquid "under conditions of fractionation, rather than equilibrium, forces the liquid more rapidly towards the base of the ($CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2) tetrahedron and thence to the ternary minimum," at which quartz will precipitate as a phenocryst phase.

The Vididalur-Vatnsdalur acid rocks bearing quartz phenocrysts appear to have originated from one-feldspar liquids of the type outlined by Carmichael (op. cit.) as their feldspar phenocrysts are often zoned continuously to rims of anorthoclase and the quartz phenocrysts appear to be of late crystallization; it seems possible, therefore, that the precipitation of the quartz phenocrysts in these rocks may have followed extreme fractionation of the feldspar components of the liquid within the system $CaAl_2Si_2O_6$ - $NaAlSi_3O_8$ - $KAlSi_3O_8$ - SiO_2. The Type 2 vein on Urdarfell is regarded as an exception to this general pattern, as it shows evidence of having formed by remelting of earlier acid material (pp 412-13).

The miarolitic cavities within the MU granophyre were usually seen to be lined by euhedral well-terminated prisms of α-quartz often set at high angles to the cavity walls; similar crystals were found forming populous encrustations on joint facies in the granophyre, such crystals reaching maximum diameters and lengths of 10 mm and 30 mm. These crystals are taken to have formed from the final hydrothermal phases of the acid material which were expelled on final cooling and contraction of the intrusion.

4-9 ACCESSORY MINERALS

1. A P A T I T E

Apatite was seen as small colourless uniaxial optically negative crystals of elongated habit and hexagonal section in all the basic rocks examined; the mineral was usually found to be scattered throughout the rock, but appeared to be particularly abundant in the small patches of salic residuum which infill the final mesh gaps in most of the eucrites, gabbros and minor intrusions. Small euhedral apatite rods up to 1 mm in length with length to breadth ratio about 20 : 1 were found scattered throughout the Hólar-Skessusaeti eucrite and these were often seen to be poikilitically enclosed by ore. Similar apatite crystals up to 1 mm in length with length to breadth ratio about 25 : 1 were found within the small patches of glassy residuum in the final mesh gaps of the Borgarvirki eucrite margins and were sometimes seen to be arranged in sheaves of parallel crystals; these sheaves appear to be similar in form to aggregates of acicular apatite crystals described from the olivine-rich basic hypabyssal intrusives of the Nuanetsi area, southern Rhodesia (Wyllie et al., 1962). Smaller acicular apatite crystals of similar proportions up to 0.5 mm in length were found to be common in the fresh glassy residua of the late set cone-sheets of Vididalsfjall, and also in the greenish patches of residual material within the early set cone-sheets and the Steinsvad and Hnjúkur gabbros.

Peck et al. (1966) studied drill cores taken from the tholeiitic basalt lava lake left by the August 1963 eruption of Kilauea Volcano, and found that apatite first formed as minute needles in interstitial glass after the precipitation of olivine, pyroxene, plagioclase and iron oxides; the apparent concentration of apatite needles in the glassy portions of the Vididalur-Vatnsdalur basic rocks suggests that these crystals are of similar late crystallization.

A few apatite needles were seen to cross the plagioclases of the basic rocks, and this mode of occurrence of apatite has been noted in Icelandic basalts by Holmes (1918, p. 192).

Acicular apatite crystals of larger size with euhedral hexagonal cross-sections were found in company with the feldspar, pyroxene and ore phenocrysts of the Hólar schliere; these apatites were often found to reach sizes of 0.5 x 0.1 x 0.1 mm and were sometimes seen to be enclosed by ore phenocrysts. A few apatites in this rock were seen to have a length to breadth ratio of about 10 : 1, but most crystals were of stumpy columnar form; these stumpy apatites are interpreted as cumulus crystals.

The marginal facies of the Urdarfell diorite contains small short columnar apatites similar to those present in the Hólar schliere; this mineral was also seen to be present as slender acicular crystals with length to breadth ratio about 20-40:1 ranging up to 2 mm in length (see Fig. 70). Apatites of both forms were found within the main diorite and the H_I rock, and some of the stumpy columnar types were seen to be partly or wholly enclosed by later-precipitated ore; in addition, some of the stumpy apatite crystals in the H_I rock were partly enclosed by the amphibole rims to pyroxene grains or the outermost rims of the plagioclase xenocrysts. A few acicular apatite crystals were found within the Urdarfell gabbro, but these appeared to be restricted to the immediate vicinity of the small patches of H_I hybrid material incorporated by the basic rock.

Apatite was found as short euhedral rods, generally up to about 0.2 mm in length with length to breadth ratios of 2-6 : 1 in the Dalsá-Urdarfell felsite, MU granophyre and the acid minor intrusions of the First and Second Phases.

Scattered small rods of apatite with similar size and elongation to those seen in the coarser-grained acid rocks were found in the glassy margin of the 50-degree sheet; these crystals were not seen to be enclosed by ore but were sometimes found to be enclosed by the ferroaugite phenocrysts. Apatites have frequently been found to be enclosed by ore minerals and clinopyroxene in the basic alkaline Chilembeni intrusion of the Nuanetsi area (Wyllie et al., 1962). The occurrence of apatites enclosed by pyroxene in the 50-degree pitchstone indicates that apatite was of relatively early crystallization in this rock.

2. Z I R C O N

Zircon appears to be rare in the basic rocks of the Vididalur-Vatnsdalur area, but a few small rods of the mineral were found in the salic residual patches of many of the eucrites, gabbros and minor intrusions examined; the apparent absence of zircon in the main fabric of these rocks and its apparent confinement to the residual patches suggests that zircon was precipitated at a late stage in the cooling history of the basic rocks. The mode of occurrence of zircon in the rocks studied thus appears to be similar to that described by Poldervaart (1956), who found that zircon crystallized after the bulk of the main constituent minerals in basaltic rocks. Zircon was found at all horizons of the Skaergaard layered series "along with the late-crystallizing minerals from the trapped intercumulus liquid" (Wager and Brown, 1968, p. 54.).

Rare small rods of pale pinkish zircon with very high relief were seen in the fine-grained acid matrix material of the Hólar schliere and the marginal facies of the Urdarfell diorite, and larger stumpy rods of similar colour up to about 0.1 mm in length were found in the acid patches of the main facies diorite and the H_I hybrid rock. A few rods in the diorite were found to have homoaxial overgrowths of colourless anistotropic material; these overgrowths may be of apatite, as Larsen and Poldervaart (1957) have described apatite crystals which contain minute zircons of early precipitation in the

Kaniksu tonalite, Idaho-Washington (op. cit; p. 555).

The zircons in the H_G granitic hybrid rock and the MU granophyre were found to be pale pink types similar in form and size to those in the intermediate rocks; these zircons are believed to be of early crystallization, by analogy with those seen in the 50-degree acid sheet. The pitchstone margins of this intrusion exemplify the status of zircon in the acid rocks studied and were found to bear rare pale pink-brown stumpy rods of zircon up to 0.1 mm in length which were sometimes seen to be partly enclosed by pyroxene phenocrysts. Zircon is thus taken to be of early precipitation in the acid rocks, and this relationship is similar to that found in acid rocks by Poldervaart (1956).

All the zircons so far described were found to show euhedral form; exact determination of the form of zircon crystals is not possible in thin section and is better carried out on rock crushes (Poldervaart, 1956.) but this was not done for the rocks studied.

Euhedral zircons in the present context are those which were not seen to show marked pitting or other evidence of dissolution. The zircons in the Type 2 acid veins which cut the Urdarfell acid and hybrid rocks were found to bear occasional zircon rods of similar form, size and colour to those in the other acid rocks; the prism facies of these vein zircons were however sometimes seen to show pitting and appeared to be corroded along small cracks transverse to the axis of elongation. A zircon rod in one of these back-veins was found to show a "waisted" form in the direction of elongation, the width of the rod decreasing almost to zero from the two ends to the mid-point of the crystal; this shape may be due to corrosion.

3. S P H E N E

Sphene was found only in the acid rocks and in the acid portions of the hybrid rocks, where it commonly occurs as small stout pale pink euhedral columns with square cross-sections and size up to 0.1 x 0.02 mm; the crystals are elongated parallel to the c-axis and typically show a "ground-glass" surface texture in thin section.

Euhedral crystals of the type described were found in the pitchstone margin of the 50-degree sheet, and were often seen to be enclosed by phenocrysts of ore and pyroxene; this indicates that the mineral was of early precipitation in the pitchstone and a similar intergrowth relationship between sphene and ore was seen in most of the sphene-bearing acid material examined.

4. E P I D O T E and A L L A N I T E

Epidote was found in most of the First Phase rocks, and was seen in the eucrites, gabbros and cone-sheets within a broad zone centred on northern Vididalsfjall (see Map 4); the mineral occurs within these rocks as small faintly pleochroic lemon-yellow crystals of anhedral form which partly replace the plagioclase and ferromagnesian minerals or as small euhedral prisms elongated parallel to the c-axis which show straight extinction and are usually associated with ragged grains of quartz, carbonate and sulphide in thin veins, patches and stringers.

Similar prismatic lemon-yellow epidotes were seen within the fine-grained acid minor intrusions of the Gálgagil vent zone, and these occur in similar small veins, patches and stringers to those found in the basic rocks; these epidotes and their accompanying minerals are believed to have been derived from the hydrothermal final phases of large basic and acid intrusions in the core zone of the Vididalur-Vatnsdalur volcano, by analogy with similar examples described from the central zones of volcanoes in other parts of Iceland (Walker, 1963; Carmichael, 1964; Sigurdsson, 1966a; Annels, 1967).

The quartz-lined miarolitic cavities in the MU granophyre were found to bear numerous euhedral prisms of lemon-yellow epidote up to about 0.2 mm in length with variable length to breadth ratios, and these crystals are commonly set in a matrix of carbonate showing occasional twin lamellae; similar epidotes associated with quartz and ore were found in small veins and nests in the parts of the Dalsá-Urdarfell felsite near to the granophyre, and it seems likely that these minerals also proceeded from the last residual part of the granophyre magma.

The spherulitic marginal facies of the MU granophyre was found to bear a few scattered euhedral stumpy prisms of golden-brown allanite up to about 0.1 mm in length which show straight extinction and marked pleochroism with maximum absorption in the direction of elongation; prisms of the same mineral were found scattered throughout the main facies of the granophyre and in the H_G granitic hybrid rock, where they were sometimes seen to be mantled by homoaxial growths of yellow epidote in similar fashion to the examples from Slaufrudal noted by Beswick (1965).

Allanite was also found in the Type 2 acid veins on south western Urdarfell; the mineral is known to occur in the Vesturhorn granophyres (Cargill et al., 1928), in the margins of the Sandfell rhyolite laccolith (Hawkes and Hawkes, 1933) and in the Austurhorn granophyres (Blake, 1966).

5. F L U O R I T E

This mineral was found only in the small quartz-epidote nests of the Dalsá-Urdarfell felsite as small anhedral pale purplish isotropic grains of fairly high relief with three cleavages intersecting at 60° and 120°. The interstitial habit of the mineral evidences its late formation in the nests. No fluorite was identified within the MU granophyre, but it may be present within this intrusion, as the analysed rock was found to contain fluorine, and fluorite occurs in the norm of this rock.

Fluorite has been found in the granophyres of eastern Iceland at Slaufrudal (Cargill et al., 1928; Beswick, 1965) and Austurhorn (Blake 1966.), in which intrusions it occurs as a late stage mineral.

B I O T I T E

This mineral was not found to be common in the rocks examined, but "beards" of very small red-brown strongly pleochroic biotite flakes were seen to fringe ore grains in parts of the Urdarfell diorite and H_I hybrid rocks; these flakes are thought to be due to late-stage reaction of the iron oxides with the surrounding quartzo-feldspathic material.

A few small scattered flakes of medium-dark brown pleochroic biotite were seen in Type 2 acid veins from Urdarfell; these flakes show typical biotite cleavages and straight extinction, and are interstitial to the alkali feldspar in the granitic vein-rock. This rock appears to show some similarities to the biotite-granites of Slaufrudal (Beswick, 1965.).

Some small irregular flakes of mica showing dark green to straw pleochroism colours were found in the H_G granitic rock; these appear to be of late formation and may be a form of biotite produced by late-stage reaction between amphibole and deuteric fluids.

No pleochroic haloes were found in any of these biotite occurrences.

6. C H L O R I T E

Chlorite was found in all the First Phase rocks and in some of the Second Phase rocks as an alteration product of ferromagnesian minerals, particularly the amphiboles in the Urdarfell hybrid rocks; in the MU granophyre this mineral was often found to form the only recognisable ferromagnesian silicate, and it may be a deuteric alteration product of amphibole, as in the hybrid rocks. The chlorite was found to have straight extinction, length-slow optical orientation, pale green pleochroism and low birefringence and is felt to be near penninite in composition.

7. G L A S S

Isotropic glass was commonly seen as an infilling to the final mesh gaps in the late set cone-sheets and allied intrusions; this feature is typical of tholeiitic rocks, (Bailey et al., 1924; Holmes and Harwood, 1929; Kennedy, 1933; Walker, Vincent and Mitchell, 1952; Yoder and Tilley, 1962) and has been described in numerous tholeiitic basalts from Iceland (Holmes, 1918, p. 192; Peacock, 1924, p. 286; Rutten and van Bemmelen, 1955, p. 168; Carmichael, 1964).

The finger-grained acid intrusions of the Vididalur-Vatnsdalur area often have glassy margins, and approximate determinations of the silica-content of five glasses from basic and acid rocks were made, by comparing the refractive indices of these glasses with the "average curve" of Huber and Rinehart (1966, Fig. 7.). This curve enables the silica-content of glasses from volcanic rocks to be determined with an accuracy of about ± 2 per cent, but Huber and Rinehart point out that a more realistic estimate can only be made by use of curves specific to given volcanic provinces (op. cit., p. 109). The values obtained are given in Table 17 together with the silica-contents of the whole rocks as determined by chemical analysis, and it can be seen that, as would be expected of residual liquids, the silica-contents of most of the glasses are higher than those of the whole rocks.

The glass in the Type 1 and 3 late set cone-sheets and related intrusions was found to be of a pale brown colour and turbid, and to bear very small comb-shaped aggregates of acicular ore crystals and occasional small acicular apatite crystals the glass of this type in the Gálgagil plug was found to have an estimated silica-content of about 56 per cent (Vi 76, Table 17). The residual patches in the First Phase rocks showed similar general features to the Second Phase glasses, but were usually entirely altered to a green or brown finely fibrous material which has been termed palagonite (Peacock, 1924, p. 286.) or chlorophaeite (Carmichael, 1964) in other Icelandic tholeiites.

The acid glasses in the Vididalur-Vatnsdalur area were seen to be pale brown to near-colourless in thin section and to contain scattered crystallites which were sometimes arranged in parallel flow trains e.g. the Breidabólsstadur pitchstone and the 50-degree pitchstone (Va 35 and Vi 178, Table 17); faint perlitic cracks were sometimes found in these glasses (see Figs. 64 and 86).

Table 17

REFRACTIVE INDICES OF GLASSES FROM THE VIDIDALUR-VATNSDALUR ROCKS

Rock type	Specimen number	n ($\pm$0.002)	SiO_2 per cent in glass (from n)	SiO_2 per cent in whole rock (from chemical analysis Table 19)
Olivine tholeiite	Vi 76	1.560	56	c.50
Black glass	Hj 3	1.519	66	64.5
Acid pitchstone	Va 35	1.496	71	71.5
Dacite	A 14	1.481	76	68.2
Acid pitchstone	Vi 178	1.483	76	67.5

CHAPTER 5.

MAJOR ELEMENT CHEMISTRY AND PETROGENESIS OF THE VIDIDALUR-VATNSDALUR ROCKS.

5-1. CHEMICAL ANALYSES.

Chemical analyses of 14 rocks were made, using the rapid methods of Henderson (1966) for SiO_2, FeO, H_2O, H_2O and CO_2, Bennett and Hawley (1965) for F, and Thomas (1966) for the remaining constituents.

The analyses and C.I.P.W. norms of the Vididalur-Vatnsdalur rocks are given in Tables 19 and 20 (key to specimens in Table 18) and they show similarities to those of the Thingmúli lavas and minor intrusions (Carmichael, 1964), in that they are usually low in alumina, magnesia and total alkalis, but are high in iron and titania; the typically high titania content of Icelandic rocks was noted by Holmes (1918). The analysed rocks, like the Thingmúli rocks, were found to follow the iron-enriched trend for British and Icelandic Tertiary tholeiitic rocks plotted by Nockolds and Allen (1956); the degree of iron enrichment shown by the Vididalur-Vatnsdalur rocks is similar to that of the Thingmúli rocks, and this trend lies between the extremely iron-rich trend of the Skaergaard rocks and the less iron-rich field of the bulk of the British Tertiary tholeiitic rocks (see Fig. 91).

5-2. VARIATION DIAGRAMS.

The analyses of the Vididalur-Vatnsdalur rocks have been plotted on variation diagrams similar to those used by Carmichael (1964), in order to effect a direct comparison with the Thingmúli series, which represents the most complete series of cogenetic Icelandic Tertiary rocks analysed to date.

TABLE 18.

KEY TO SPECIMENS ANALYSED.

First Phase.

1	Hg 1.	Feldsparphyric main facies eucrite of Hólar intrusion.
2	Vi 419.	Urdarfell gabbro.
3	Hg 2.	Lower marginal dolerite, Hólar intrusion.
4	Vi 265/14	H_I intermediate hybrid, southwestern Urdarfell.
5	Vi 178.	Blue pitchstone margin of the 50-degree acid intrusion south of Raudkollur.
6	Vi 615.	H_G granitic hybrid, southwestern Urdarfell.
7	Vi 39.	Dalsá-Urdarfell felsite.
8	Vi 40.	Main facies of MU granophyre.
9	Vi 214.	Type 2 acid vein, southwestern Urdarfell.
14	Va 35.	Black pitchstone from margin of Breidabólsstadur acid intrusion.

Second Phase.

10	Sf 2.	Type 1 late-set olivine-tholeiite cone-sheet from Sandfell (777 m.) ridge.
11	HjL	Olivine-free tholeiite from Hjallin lens.
12	C 1b	Olivine-free thóleiite inclusion from Gálgagil acid-basic composite intrusion.
13	A 14.	Glassy dacite from upper edge of central portion of Gálgagil composite intrusion.

TABLE 19.

CHEMICAL ANALYSES OF ROCKS FROM THE VIDIDALUR-VATNSDALUR AREA.

Analyst: R.N. Annells (*D.G. Powell) (†Miss S.A. West)

See Table 18 for key to specimens

	FIRST PHASE ROCKS										SECOND PHASE ROCKS			
	1	2	3	4	5	6	7	8	9	14	10	11	12	13
SiO_2	46.54	41.70	47.70	59.95	67.54	68.60	70.50	74.66	76.5	71.5	49.75	47.60	50.3	68.20
TiO_2	1.05	3.5	3.0	1.6	0.27	0.33	0.4	0.25	0.1	0.2	2.9	3.2	3.0	0.3
Al_2O_3	19.40	13.9	13.2	14.5	12.1	13.56*	13.0	12.42	11.9	12.4	14.0	14.0	14.4	11.3
Fe_2O_3	3.8	7.4	6.1	3.64	1.56	1.00	2.5	0.12	1.6	0.7	3.3	3.1	4.0	2.73
FeO	4.5	10.5	8.8	5.3	2.7	3.1	1.1	2.8	0.4	1.1	10.7	12.6	10.54	2.3
MnO	0.11	0.26	0.3	0.25	0.16	0.17	0.13	0.12	0.06	0.06	0.32	0.32	0.33	0.18
MgO	5.24	6.9	4.9	1.2	0.17	0.13	0.61	0.16	0.53	0.4	5.9	3.8	3.53	0.4
CaO	14.1	11.8	11.9	5.9	1.7	1.53	1.3	1.21	0.15	1.7	7.0	10.00	7.3	3.3
Na_2O	2.8	2.5	2.8	3.16	5.4	5.63	5.3	4.55	3.82	3.8	2.97	3.14	3.7	4.35
K_2O	0.18	0.16	0.2	1.85	0.9	3.2	2.6	3.1	3.6	3.3	0.94	0.8	0.9	1.2
P_2O_5	0.11	0.2	0.3	1.05	0.01	0.05	0.01	0.04	0.02	0.08	0.9	0.5	0.4	0.01
H_2O^+	1.1	0.7	0.7	0.5	3.6	0.4	0.20	0.3	0.15	3.9	0.6	0.4	0.42	2.6
H_2O^-	0.6	0.33	0.25	0.2	3.7	0.2	0.05	0.1	0.04	0.53	1.3	0.5	0.5	2.2
CO_2	-	0.2	0.12	0.9	-	0.9	-	-	0.15	-	-	-	-	0.56
F	-	-	-	-	-	-	0.14†	0.05†	-	0.06†	-	-	-	-
Totals:	99.53	100.05	100.27	100.00	99.86	98.83	97.84	99.38	99.02	99.73	100.58	99.96	99.39	99.83
$\frac{(Fe''' + Fe'' + Mn)100}{Fe''' + Fe'' + Mn + Mg}$	46.2	58.7	62.4	81.0	93.5	94.8	76.5	93.5	-	70.9	57.0	69.8	69.5	87.5
Molecular normative $\frac{(Ab + Or)100}{Ab + Or + An}$	39.6	47.4	53.8	66.5	89.8	96.9	94.2	93.0	-	88.1	59.3	63.7	66.2	85.3
$\frac{FeO}{Fe_2O_3}$	1.18	1.42	1.45	1.46	-	-	-	-	-	-	3.24	4.02	2.70	-

TABLE 20.

C.I.P.W. NORMS OF ROCKS FROM THE VIDIDALUR-VATNSDALUR AREA. (See Table 18 for key to specimens).

	FIRST PHASE ROCKS										SECOND PHASE ROCKS			
	1	2	3	4	5	6	7	8	9	14	10	11	12	13
Qz														
Or	-	-	3.34	21.58	27.54	19.38	27.04	31.87	39.60	32.76	3.57	-	3.15	31.73
Ab	1.10	0.94	1.11	10.82	5.56	18.90	15.57	18.18	21.13	19.46	5.56	5.00	5.39	7.23
An	20.01	16.92	23.83	26.83	45.54	47.42	44.54	38.51	32.17	31.96	25.00	26.61	31.44	36.68
Ne	39.78	26.04	22.66	19.81	6.15	2.25	3.89	4.45	0.75	7.23	22.04	21.46	19.82	7.78
Cor	1.93	2.36	-	-	-	-	-	-	-	-	-	-	-	-
Di Wo	-	-	-	-	-	-	-	-	1.50	-	-	-	-	-
Di En	13.94	13.20	14.50	1.04	1.03	2.13	-	0.43	-	-	2.98	10.26	5.65	-
Di Fs	8.74	8.47	8.90	0.42	0.11	1.84	-	0.04	-	-	1.53	3.90	2.43	-
Wo	2.38	3.83	4.75	0.66	1.03	2.24	-	0.44	-	-	1.37	6.53	3.21	-
Hy En	-	-	-	-	-	-	0.4	-	-	-	-	-	-	3.60
Hy Fs	-	-	3.40	2.48	0.31	1.60	1.5	0.40	1.30	1.00	12.70	3.49	6.37	1.00
Ol Fo	-	-	1.85	3.91	2.57	0.24	-	4.32	-	1.16	11.35	5.85	8.41	1.74
Ol Fa	3.22	6.16	-	-	-	-	-	-	-	-	-	1.47	-	-
Mt	0.92	3.06	-	-	-	-	-	-	-	-	-	2.71	-	-
Hm	5.57	10.73	8.82	5.34	2.23	1.39	3.71	0.23	1.25	0.93	4.87	4.41	5.8	4.01
Il	-	-	-	-	-	-	-	-	0.74	-	-	-	-	-
Ap	1.98	6.69	5.78	3.04	0.52	0.61	0.15	0.53	0.15	0.46	5.47	6.08	5.78	0.61
Sph	0.34	0.34	0.67	2.52	tr	0.17	tr	0.20	tr	0.30	2.02	1.34	1.01	0.03
Fl	-	-	-	-	-	-	0.31	-	-	-	-	-	-	-
H_2O	-	-	-	-	-	-	0.14	0.10	-	0.14	-	-	-	-
Rest	1.14	0.71	0.68	0.50	3.61	0.4	0.20	0.30	0.15	3.90	0.60	0.40	0.42	2.60
Total	0.56	0.56	0.37	1.08	3.70	1.1	0.05	0.10	0.19	0.53	1.50	0.50	0.50	2.76
	101.61	100.01	100.67	100.03	99.95	99.67	97.50	100.10	98.93	99.83	100.56	100.01	99.38	99.77

The material selected for analysis was chosen as being that material most likely to represent relatively unfractionated liquids e.g. the glassy or fine-grained margins of minor intrusions, but, as is apparent from their mineralogy (Chapter 4) the Vididalur-Vatnsdalur rocks are highly fractionated types, often showing evidence of disequilibrium in bearing highly zoned plagioclase as phenocrysts and groundmass crystals; in addition, most of the rocks found are porphyritic, bearing phenocrysts or xenocrysts of plagioclase, pyroxene, olivine and ore so that their analyses tend to scatter somewhat loosely about the established Thingmúli and Skaergaard liquid lines of descent.

The numbering of Tables 18-20 is used throughout the text and diagrams of this chapter, individual Vididalur-Vatnsdalur specimens being referred to by numbers in parentheses.

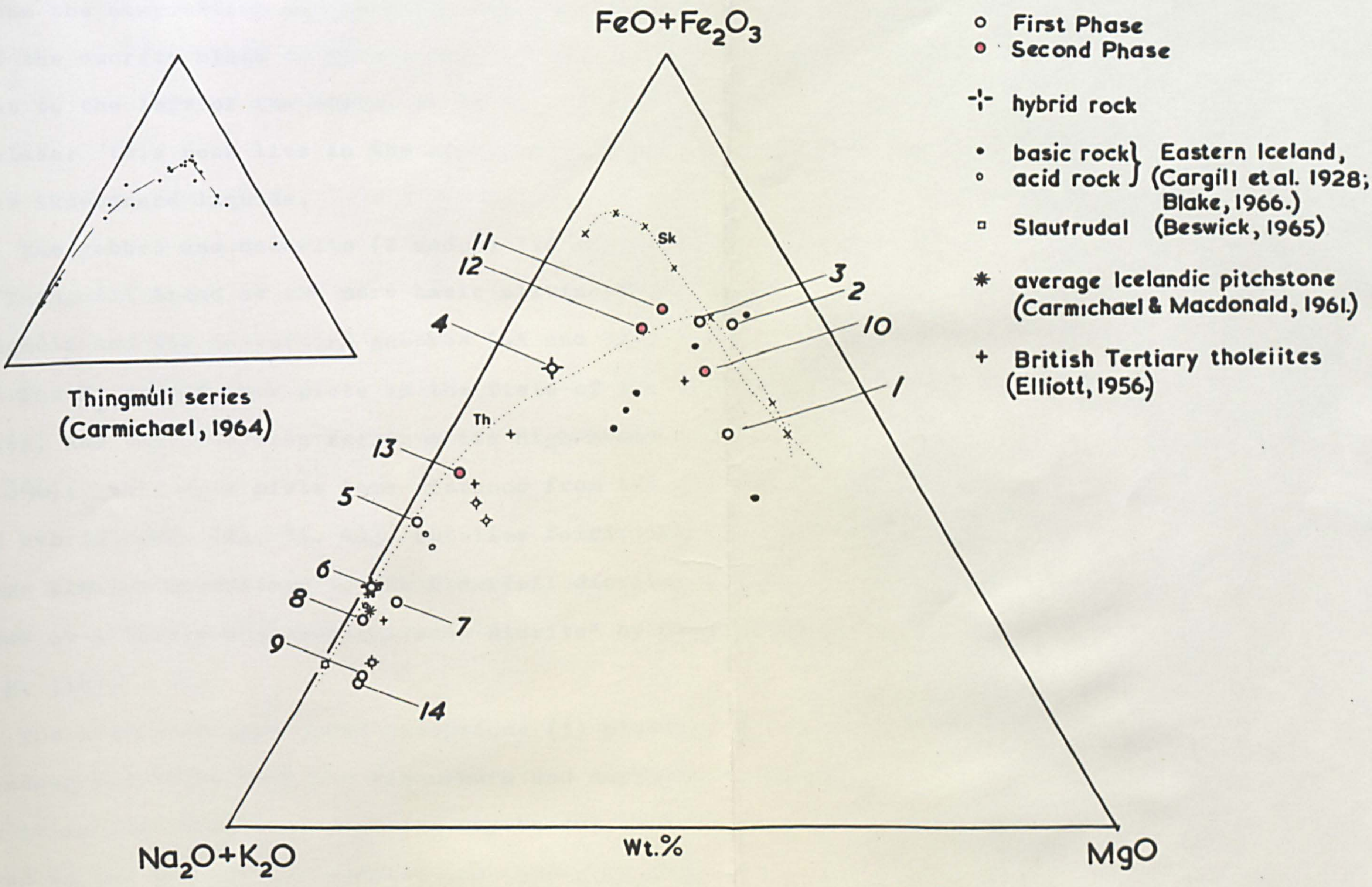
The analyses of individual rocks sometimes show similarities with those of the Thingmúli rocks and other Tertiary rocks from the literature. The Thingmúli analyses are referred to by the numbers used by Carmichael (1964, Tables 2-6) in the original account and are not tabulated in the present work; other analyses of Icelandic and British Tertiary rocks are tabulated in Part 2, Table A of the Appendix and are mentioned in the text where relevant by numbers with the suffix "A".

1. <u>FMA diagram (see Fig. 91).</u>

This diagram was plotted from oxide data recalculated to 100 per cent; the Thingmúli plot is shown as an inset.

<u>First Phase Rocks.</u>/

Fig. 91. FMA (wt. %) plot of the analysed Vididalur-Vatnsdalur rocks (large circles, Second Phase rocks in red); specimen numbers as in Table 18. The positions of some intrusive rocks from eastern Iceland and the British Tertiary Province are also shown, and their analyses are given in Part 2 of the appendix. The Thingmuli trend (Th) is also shown and the series is plotted in the small inset triangle. The Skaergaard trend (Sk) and liquids (crosses) are taken from Wager (1960).



Thingmúli series
(Carmichael, 1964)
FeO+Fe2O3
Na2O+K2O
Wt.%
MgO
Sk
Th
1
2
3
4
5
6
7
8
9
10
11
12
13
14
First Phase
Second Phase
hybrid rock
basic rock
acid rock
Eastern Iceland, (Cargill et al. 1928; Blake, 1966.)
Slaufrudal (Beswick, 1965)
average Icelandic pitchstone (Carmichael & Macdonald, 1961.)
British Tertiary tholeiites (Elliott, 1956.)

First Phase Rocks.

The points for the analysed rocks fall on the Thingmúli curve and the composition of the Hólar eucrite (1) lies close to that of the eucrite block 27 from a tuff at Thingmúli and lies somewhat to the left of the curve, as it is accumulative in plagioclase; this rock lies in the approximate region of the earliest Skaergaard liquids.

The gabbro and dolerite (2 and 3) lie on the same part of the Thingmúli trend as the more basic olivine-free tholeiites of Thingmúli and the Austurhorn gabbros (6A and 7A).

The H_I hybrid rock plots in the field of the Thingmúli andesites, and this position reflects its high modal andesine and ore (p.396); this rock plots some distance from the eastern Iceland hybrid rocks (2A, 3A, 4A), but lies fairly near to 2A, which has similar mineralogy to the Urdarfell diorite, and is described as a "basic quartz-hornblende diorite" by Cargill et al., (1928, p. 514).

The 50-degree sheet blue pitchstone (5) plots near to the hornblende-granophyres from the Vesturhorn and Austurhorn (4A and 5A) but it is felt that this position may be due to relatively high iron in the form of ferroaugite and iron-rich olivine phenocrysts and also to possible removal of potash from the glass during hydrothermal alteration in the manner suggested by Carmichael (1962, p. 257); thus the original rock might have plotted nearer to the position of the granophyres.

The Dalsá-Urdarfell felsite (7) lies away from the granophyres due to its relatively high magnesia content; this rock bears 0.61 per cent MgO, compared to 0.16 per cent in the MU granophyre, and the range of 0.02-0.24 per cent MgO found in the pitchstones, rhyolites and granophyres of Thingmúli, (Carmichael, 1964, Table 5). The relatively high magnesia in this rock may be contained in the clinopyroxene phenocrysts.

The MU granophyre and the H_G hybrid rock (6 and 8) plot close to the other analysed acid rocks from eastern Iceland, and their analyses show similarities to those of the Austurhorn granophyres 11A and 12A, the average Icelandic pitchstone 15A of Carmichael and MacDonald (1961) and the acid rocks 18-24 of Thingmúli (Carmichael, 1964).

The analyses (6) and (8) also plot close to that of the Glen Shurig pitchstone of Arran (19A, indicated by an upright cross), but are not so alkali-rich as the average granophyre of Slaufrudal (14A).

The Type 2 acid vein (9) plots in the same area as the average Slaufrudal hybrid rock (13A) and shows a relatively high magnesia content for such an alkali-rich granitic rock; this may be continued in the scattered amphibole and biotite grains within the rock.

Second Phase Rocks.

The fine-grained analysed rocks of this phase show close correspondence to the Thingmúli trend. The olivine-tholeiite cone-sheet (10) plots to one side of the main trend line, being somewhat accumulative in plagioclase, but occupies a similar position to that of a porphyritic dyke from Thingmúli and the olivine-tholeiites from the same area; this plot also lies close to that of the Cleveland tholeiite, of Teesdale, Northern England (16A).

The two olivine-free tholeiites (11 and 12) plot close to the similar olivine-free tholeiites of Thingmúli, and represent the greatest level of iron enrichment found in the analysed Vididalur-Vatnsdalur rocks; these two tholeiites also have a higher total iron content than the two tholeiite specimens from a basic pillow in the net-veined complex of the Austurhorn intrusion (8A and 9A).

The Gálgagil dacite (13) lies at about the same position as the most acid Thingmúli andesites, and this position is close to that of the Ardnamurchan inninmorite (18A). The Breidabólsstadur pitchstone (14) lies nearer to the M corner of the diagram than the other acid rocks and its relatively high magnesia content (0.4 per cent weight MgO) may be concentrated in the hypersthene phenocrysts present in the rock (p. 361). It is of interest to note that this rock plots near to the acid vein (9) and the average Slaufrudal hybrid rock 13A (Beswick, 1965).

2. <u>$FeO+Fe_2O_3/FeO+Fe_2O_3+MgO$ vs. SiO_2 diagram (Fig. 92).</u>

The Skaergaard differentiation trend and the Thingmúli trend and plots are shown in this diagram, which shows the same

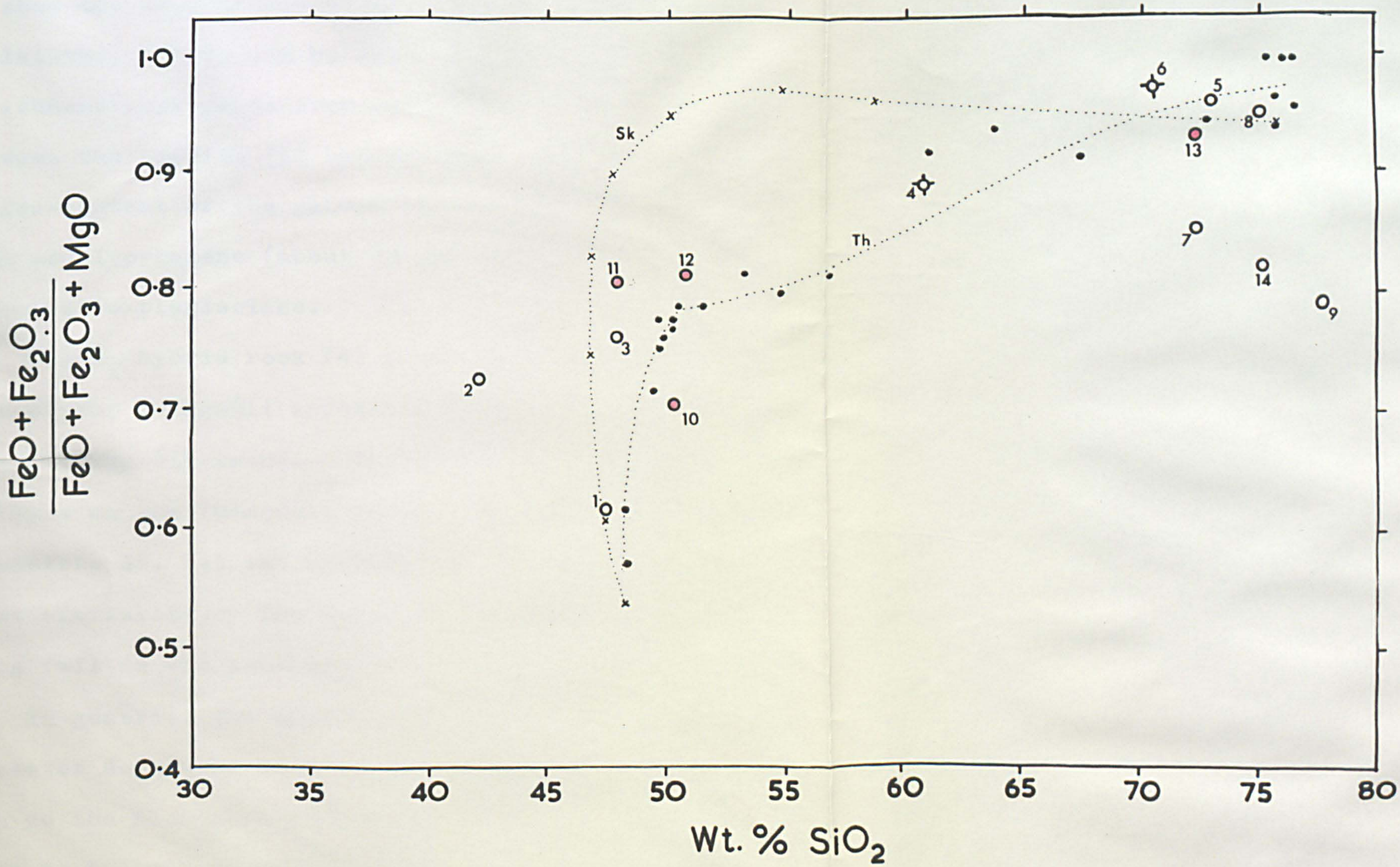


Fig. 92. Plot of the ratio $FeO+Fe_2O_3/FeO+Fe_2O_3+MgO$ against silica for the Vididalur-Vatnsdalur rocks (symbols as in Fig. 91); the specimen numbers are as in Table 18 and the ratios are calculated from recalculated dry analyses. The Thingmuli rocks (small solid circles) and trend (Th) are shown for comparison and are taken from Carmichael (1964); the Skaergaard liquids (crosses) and trend (Sk) are from Wager (1960).

general relationships between the three sets of rocks as in Fig. 91 and is plotted from recalculated water-free analyses.

The First Phase eucrite dolerite and gabbro (1, 2 and 3) show the same degree of iron-enrichment as the Thingmúli tholeiites, and it can be seen that the initial stages of this enrichment took place over only a small change in silica content between the eucrite (1) and dolerite (3). The apparently low silica-content of the gabbro (2) is believed to be due to its high modal pyroxene (about 35 per cent by volume) and ore relative to plagioclase.

The H_I hybrid rock (4) plots in a similar position to that of the Thingmúli andesites (as in Fig. 91), and lies close to the Thingmúli trend. The 50-degree sheet blue pitchstone (5) lies on the Thingmúli trend line close to the Thingmúli pitchstone 18, but the analyses of these two rocks do not show great similarity. The H_G, rock (6) and the MU granophyre (8) plots fall in the same area as the Thingmúli pitchstones.

In general, the analyses of the Second Phase rocks show a greater degree of similarity to those of the Thingmúli rocks than do the First Phase rocks. The olivine-tholeiite (10) lies close to the olivine-tholeiite 3 of Thingmúli, and the analyses of these two rocks show noticeable similarity, the Thingmúli rock, however, having higher lime and lower potash than (10).

The olivine-free tholeiites (11) and (12), plot near to the olivine-free tholeiites of the Thingmúli series, and their analyses lie in the range of compositions shown by these rocks.

The analysis of the dacite (13) has higher Fe_2O_3 and MgO than the Thingmúli pitchstone 18 near to which it plots, and the relatively high magnesia content of the pitchstone (14) again places its plot below the main trend, although its silica content is similar to that of the acid rocks of Thingmúli.

As can be seen by comparison of the respective analyses, this variation diagram tends to exaggerate the differences between the more silicic Vididalur-Vatnsdalur and Thingmúli rocks.

3. Normative Feldspar Diagram (Fig. 93, Table 21).

This diagram demonstrates the difference in potash content of the analysed First and Second Phase rocks and is plotted from the data of Table 21, in which the normative feldspar constituents of the analysed rocks have been recalculated to 100 per cent.

The eucrite, gabbro, and dolerite (1, 2 and 3) of the First Phase appear on this diagram in the same order as in Figs. 91 and 92; their normative anorthite content is rather lower than that of the plagioclases determined by optical methods, and this is felt to be due to the extensive range of zoning found in the plagioclases of these rocks. The low potash content of these First Phase basic rocks is reflected in the closeness of the plots to the albite-anorthite side of the triangle.

The points for the acid rocks group closely about the trend for analysed feldspar phenocrysts of Icelandic rocks (Carmichael, 1963b) and lie within the anorthoclase field; these feldspar compositions show some correspondence with the optically determined compositions of the feldspars of these acid rocks.

The position of the H_I rock (4) beyond the limit of ternary solid solution in natural feldspars is felt to be due to its hybrid nature; the feldspar in this rock consists of a non-equilibrium mixture of calcic andesine and anorthoclase (as micropegmatite) and the presence of the alkali feldspar would tend to displace the plot towards the orthoclase apex. The normative feldspar constituents of the two dioritic hybrid rocks from the Vesturhorn (2A and 3A) are plotted for comparison and these are also displaced towards the orthoclase apex, presumably as a result of the presence of alkali feldspar in graphic intergrowth with quartz; in the interstices of a labradorite-andesine fabric.

All the First Phase acid rocks plot on the albite side of the alkali feldspar minimum; none are as potassic as those of the palingenic acid vein (9).

The Second Phase tholeiites (10, 11 and 12) are grouped closely together about the limit of ternary solid solution in the same order as that in which they appear in Figs. 91 and 92; it is clearly seen that these points lie closer to the orthoclase apex than do those of the First Phase rocks, and inspection of the analyses of the basic rocks of the two Phases reveals the higher potash content of the Second Phase basic rocks (see Table 19).

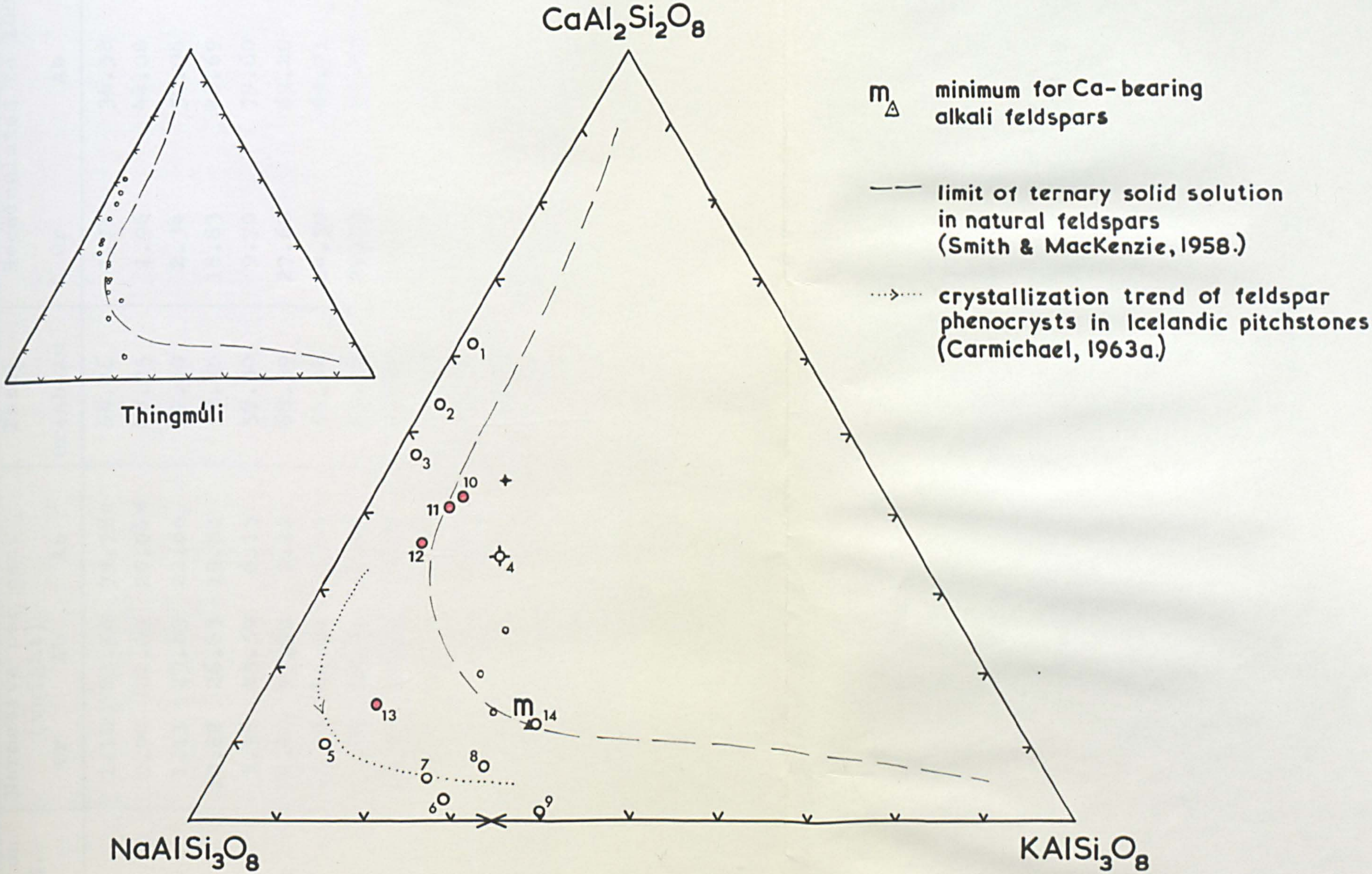


Fig. 93. Plot of the recalculated normative feldspar components of the Vididalur-Vatnsdalur rocks and some intrusive rocks from eastern Iceland (see Table 21); the symbols and numbers used are the same as those in Fig. 91 and Table 18. The minimum (m) for calcium-bearing alkali feldspars and the alkali feldspar minimum (M) are taken from Tuttle and Bowen (1958). Plots of the normative feldspar components of the Thingmuli series are shown on the small triangle, taken from Carmichael (1967b).

Table 21. NORMATIVE FELDSPAR CONSTITUENTS (RECALCULATED TO 100 per cent) OF THE ANALYSED VIDIDALUR-VATNSDALUR ROCKS. (see Fig. 93).

Number on Fig. 93.	Normative per cent (weight)			Total	Recalculated to 100 per cent		
	Or	Ab	An	Or+Ab+An	Or	Ab	An
1	1.10	23.58	39.78*	64.46	1.71	36.58	61.71
2	0.94	21.27	26.04*	48.25	1.96	44.08	53.96
3	1.11	23.83	22.66	47.60	2.34	50.06	47.60
4	10.82	26.83	19.81	57.46	18.83	46.69	34.48
5	5.56	45.59	6.15	57.30	9.70	79.60	10.70
6	18.90	47.47	2.22	68.59	27.60	69.20	3.20
7	15.56	44.64	3.84	64.04	24.30	69.71	5.99
8	18.18	38.51	4.45	61.14	29.73	62.99	7.28
9	21.13	32.20	0.75	54.08	39.10	59.50	1.40
10	5.56	25.00	22.04	52.60	10.57	47.53	41.90
11	5.00	26.61	21.46	53.07	9.42	50.14	40.44
12	5.39	31.44	19.82	56.65	8.80	55.50	35.70
13	7.23	36.68	7.78	51.69	13.99	70.96	15.05
14	19.46	31.96	7.23	58.65	33.18	54.49	12.33

*corrected for normative nepheline

The Gálgagil dacite (13) lies in the field of the lime anorthoclases (Muir, 1962) and this may be due to the rather high lime content of the rock which is believed to be due to the introduction of lime into the acid rock from the basic component of the Gálgagil composite intrusion (see p.515).

The Breidabólsstadur pitchstone (14) plots near to the ternary minimum for calcium-bearing alkali feldspars.

4. Albite ratio vs. Iron ratio diagram (Fig. 94).

This diagram is plotted using the same parameters as those used by Carmichael (1964) in the modified form of the original diagram (Wager, 1956) and the Thingmúli plots are shown for comparison; individual units in the iron ratio are calculated from the relation: Weight per cent of element/ Atomic weight of element, and the iron and albite ratios are given in Table 19.

The main value of this type of diagram is that it allows representation of individual rocks in terms of the constituents of their plagioclase and ferromagnesian minerals, these minerals being the most sensitive indicators of the fractionation stage of basaltic liquids.

The points for the First Phase rocks group closely about the trend for the Skaergaard rocks (see Fig. 94). The eucrite (1) plots near to the Skaergaard HZ liquid and as the composition of the first plagioclase to precipitate from the eucrite liquid lies near to that of the estimated composition of the HZ plagioclase (An_{78}, see p.472), the chemical

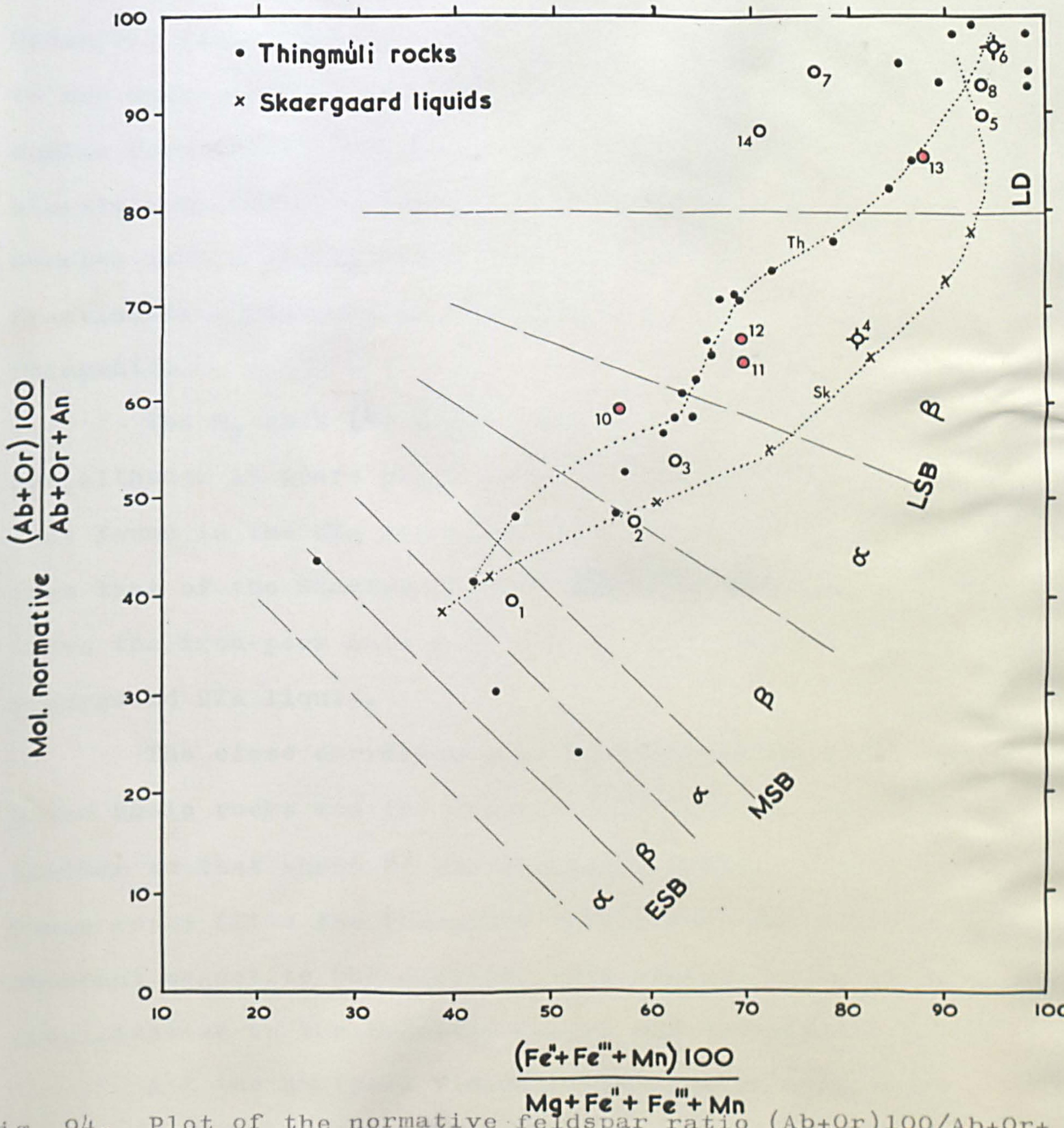


Fig. 94. Plot of the normative feldspar ratio (Ab+Or)100/Ab+Or+An against the atomic ratio (Fe'''+Fe''+Mn)100/Mg+Fe''+Fe'''+Mn for the Vididalur-Vatnsdalur rocks (symbols as in Fig. 91); the data is taken from Table 19. The Thingmúli rocks (small solid circles) and trend (Th) are shown for comparison and are taken from Carmichael (1964). The Skaergaard liquids (crosses and trend) (Sk) are taken from Wager (1960) and the fractionation stages are from Wager (1956).

similarity of the two types is considered to be real. The Urdarfell gabbro (2) and the Hólar dolerite (3) plot close to the Skaergaard LZ liquid and the plagioclase and calcic augite compositions of these two rocks (see Fig. 51) are closely comparable to those of the Skaergaard type. The eucrite gabbro and dolerite also plot in the same part of the fractionation sequence as the more basic tholeiites of Thingmúli.

The H_I rock (4) plots near to the Skaergaard trend, but although it bears plagioclase of similar composition to that found in the UZa rocks, its augite is more magnesian than that of the Skaergaard rock [redacted] and Fig. 91 shows the iron-poor nature of the H_I rock relative to the Skaergaard UZa liquid.

The close correspondence in composition of the First Phase basic rocks and the Skaergaard HZ and LZ liquids is similar to that shown by the Thingmúli rocks. These First Phase rocks (like the Thingmúli rocks) were not found to bear abundant magnetite phenocrysts, this mineral being of late precipitation in the eucrite, gabbro and dolerite.

All the analysed Vididalur-Vatnsdalur acid rocks except the felsite (7) show high albite and iron ratios so that they plot in the same area of the diagram as the Thingmúli acid rocks; the albite ratio of the felsite is similar to that of the other acid rocks, but is displaced to the left of these plots due to its relatively high magnesia content.

The Second Phase rocks lie close to the Thingmúli rocks and, as has already been mentioned, comparison of the analyses of the two groups reveals real chemical similarities. The analysed Vididalur-Vatnsdalur tholeiites plot in the same order as that in which they appear in Figs. 91, 92 and 93 and they lie in the same part of the field as the Thingmúli tholeiites, the two olivine-free tholeiites (11 and 12) plotting as later liquids than the olivine-tholeiite (10). These analysed Second Phase basic rocks are felt to approach more nearly to true liquids than do the First Phase basic rocks, as they were found to bear only sporadic phenocrysts. The noticeable separation between the plots of the First and Second Phase basic rocks (see especially points (3), (10), (11) and (12)) is felt to reflect the higher potash content of the latter group, which gives their albite ratios slightly higher numerical values than those of First Phase rocks of broadly similar silica, magnesia and total iron content. This difference in potash content has already been pointed to in the discussion of the normative feldspars of the First and Second Phase rocks.

The dacite (13) plot lies on the Thingmúli trend near to the Thingmúli andesite 17, and its potash content (1.2 per cent) and lime content (3.3 per cent) are more typical of Icelandic andesitic than of rhyolitic rocks; these figures may be due to added lime derived from the basic components of the composite intrusion of which the dacite forms a part. It is thought that this extra lime is an expression of the abundant andesine (An_{30}) crystals present in the rock, and it seems unlikely that potash has been leached from the dacite as the rock is not hydrothermally altered. The high silica and water contents of the dacite, together with its relatively low total iron figure, are more similar to those of the acid pitchstones of Thingmúli than to the andesites.

The acid pitchstone (14) bears a phenocryst assemblage of hypersthene, ferroaugite and andesine (see p. 360) apparently more appropriate to an Icelandic andesite than to a rhyolitic rock, and the relatively high magnesia and lime concentrations in these minerals are believed to be responsible for the low albite and iron ratios which displace the plot of this rock to the left of the main Thingmúli trend. The plots of this pitchstone (14) fall consistently away from the other acid rocks in Figs. 91 and 92; and in each case, the direction of displacement is consistent with relative enrichment in magnesia.

5. Normative Albite-Orthoclase-Quartz Diagram (Fig. 95, Table 22).

This figure has been plotted using data from the analysed acid and hybrid rocks in which the normative albite+orthoclase+quartz forms more than 75 per cent of the norm; these totals have been recalculated to 100 per cent (see Table 22). It will be seen from these data that albite, orthoclase and quartz account for over 80 per cent of the norm in the

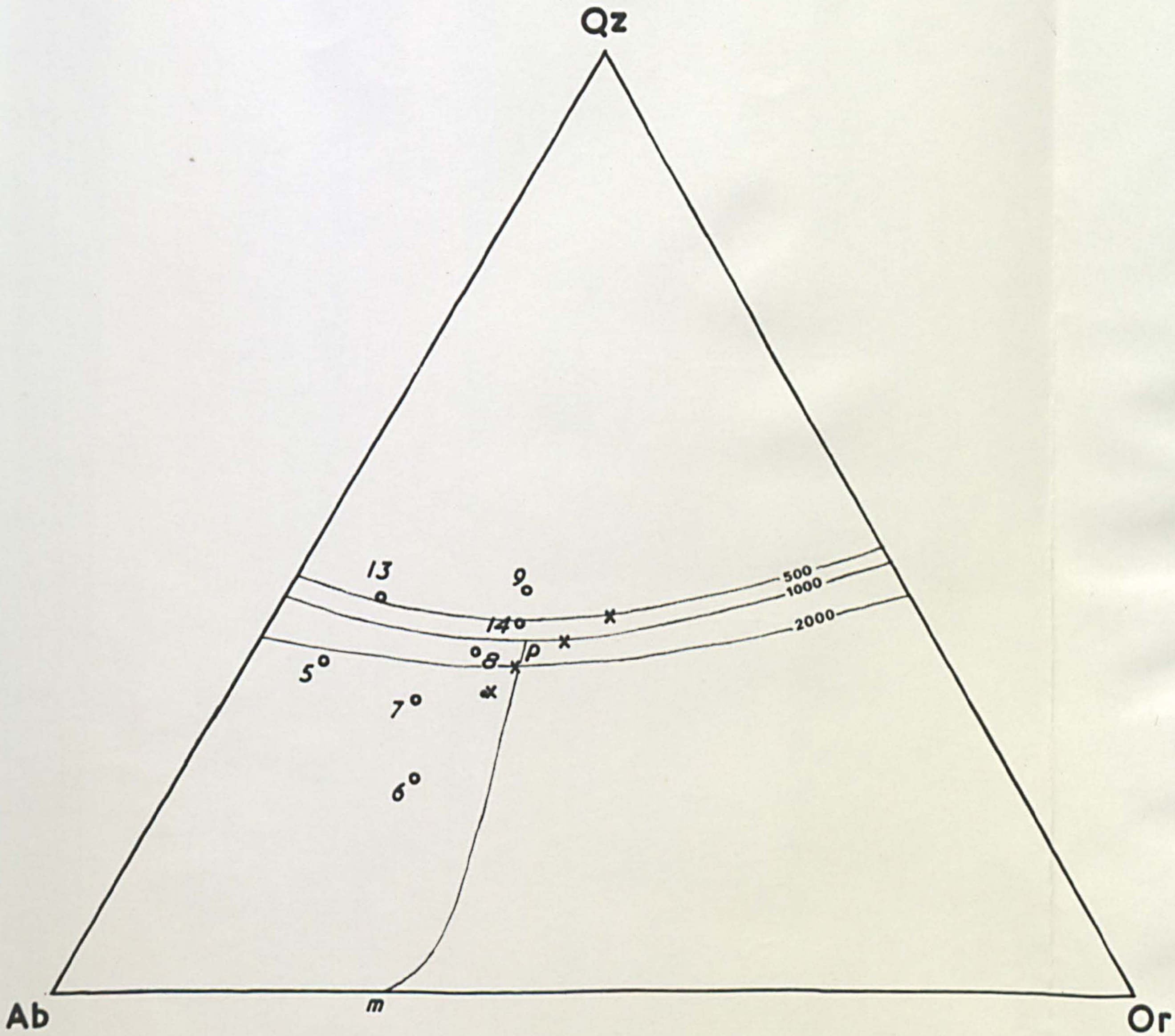


Fig. 95. Plot of the normative albite-orthoclase-quartz ratios (wt. %) of the acid rocks listed in Table 22. The quartz feldspar boundaries at water-vapour pressures of 500, 1000, and 2000 kg/cm^2 and the isobaric temperature minima for these pressures and 3000 kg/cm^2 (crosses) are taken from Tuttle and Bowen (1958, Figs. 22, 23 and 24). The line pm represents the feldspar thermal valley for a water-vapour pressure of 1000 kg/cm^2 (Tuttle and Bowen, 1958, Fig. 30). Symbols as in Fig. 91.

Table 22.

NORMATIVE ALBITE, ORTHOCLASE AND QUARTZ OF THE VIDIDALUR-VATNSDALUR ROCKS PLOTTED IN Fig. 95.

Number on Fig. 95	Rock type	Normative per cent (weight)			Total	Recalculated to 100 per cent		
		Qz	Or	Ab	(Qz+Or+Ab)	Qz	Or	Ab
13	Dacite, Gálgagil intrusion.	31.73	7.23	36.68	75.64	42.0	9.5	48.5
5	Blue pitchstone, 50-degree sheet.	27.54	5.56	45.59	78.69	35.0	7.1	57.9
14	Pitchstone, Breidabólsstadur.	32.76	19.46	31.96	84.18	38.9	23.1	38.0
6	Granitic hybrid (H_G) Urdarfell.	19.38	18.90	47.42	85.70	22.6	22.1	55.3
7	Felsite, Dalsá.	27.04	15.57	44.54	87.15	31.0	17.9	51.1
8	MU granophyre.	31.87	18.18	38.51	88.56	36.0	20.5	43.5
9	Acid vein, Urdarfell	39.6	21.13	32.17	92.90	42.6	22.8	34.6

granophyres, in similar fashion to the high totals of these normative minerals found in the Tertiary granophyres and granites of Skye and Rhum (Brown, 1963, Table 1).

All the Vididalur-Vatnsdalur acid and hybrid rocks analysed plot in the albite field to the left of the line "pm" on Fig. 95 (the feldspar thermal valley at 1000 kg/cm^2.), and the isobaric temperature minima (crosses) which are taken from Tuttle and Bowen (1958). The position of the plotted points is consistent with the higher content of soda relative to potash in these and other Icelandic acid rocks (Carmichael, 1963b; Beswick, 1965). The confinement of these points to the albite field may also indicate that the Vididalur-Vatnsdalur acid rocks were produced by differentiation of tholeiitic magma by analogy with the similar distribution of the normative albite-orthoclase quartz plots of the Thingmúli and Skaergaard series (Carmichael, op. cit., p. 126; Wager and Brown, 1968, p. 142).

The H_G rock (6) lies relatively near to the albite corner of the diagram, due to its relatively high normative albite content which is expressed as modal albitic plagioclase (An_5) and anorthoclase. The blue pitchstone (5) bears relatively high normative albite, and this is felt to be due to the presence of sodic plagioclase zoned to anorthoclase, and the possible effect of leaching of potash from the residual glass by regional hydrothermal alteration in the manner suggested by Carmichael (1962).

The Dalsá felsite (7) plot shows it to be more sodic than the MU granophyre (8), and the two rocks have similar normative Qz+Or+Ab totals (see Table 22); their relative positions on the diagram show the more fractionated nature of the granophyre compared to the felsite, as suggested by their field relationships and petrography. The granophyre (8) bears quartz phenocrysts, indicating that it lies in the feldspar - quartz field boundary or within the quartz field, and Fig. 95 shows that it would lie on this boundary at a water vapour pressure of about 1500 kg/cm^2, in similar fashion to the Beinn an Dubhaich granite of Skye and a felsite from Rhum (Brown, 1963, Table 1 and Fig. 1, nos. 11 and 14); these two Hebridean rocks are both from small high-level intrusions. The field and petrographic evidence of the marginal facies indicates that the MU granophyre was emplaced as a liquid bearing phenocrysts of low-transitional andesine, pyroxene, fayalitic olivine and β-quartz (in their probable order of crystallization). The chemical and mineralogical evidence indicates that the plagioclase and quartz phenocrysts of the MU granophyre were precipitated under relatively high water vapour pressures and this is believed to be the result of crystallization of acid material at low to intermediate crustal levels. The apparently high-pressure position of the quartz-feldspar boundary curve indicates that the granophyre is a high melting-temperature type, and this is further evidenced by its liquidity on emplacement as reflected by its ability to chill against, and vein the country rocks; the MU granophyre shows similarity in these features to the high melting-temperature Beinn Dearg Mhor granophyre of Skye investigated by Brown (1963, p. 551), which does not, however, contain quartz phenocrysts. Further evidence of the high water vapour pressure under which the MU granophyre began crystallization is given by the presence of numerous miarolitic cavities (see p. 207) and occasional breccia zones (see p. 208) which point to the rapid release of a high proportion of tightly-confined dissolved water on emplacement of the magma at a low-pressure crustal level (Wager et al., 1965). The apparent presence of tridymite in the outer parts of the spherulites of the chilled marginal granophyre is taken to indicate that this part of the intrusion chilled rapidly under very low pressure; this rock lies at a structural level about 400-500 m below the probable land surface of the time represented by the base of the Hvammur tuff on Krossdalskúla.

In summary, the available evidence is believed to suggest that crystallization of the MU granophyre began at moderate depth under fairly high water vapour pressures, ore and andesine being the first minerals to precipitate as phenocrysts; followed by pyroxene, fayalite and quartz. After precipitation and initial growth of the β-quartz phenocrysts the liquid and suspended phenocrysts were rushed upwards to a low-pressure level of the crust, where the magma locally chilled against and veined the country rock, the phenocrysts being surrounded by rapidly formed spherulites. The more slowly-cooled inner part of the magma body was apparently still hot enough to form a welded contact with the previously intruded Dalsá felsite and the remaining interstitial liquid produced more sodic rims to the plagioclase phenocrysts and finally crystallized as graphic intergrowths of anorthoclase and α-quartz. The sodic plagioclases underwent partial peristeritic unmixing during the later stages of cooling (see p. 481).

The acid vein (9) lies in the silica field on Fig. 95 and was found to bear occasional bipyramidal β-quartz crystals of early precipitation. The maximum depth at which this vein would have crystallized is suggested by its distance below the top of the lava pile, and the apparent absence of tridymite from the rock; the vein lies at about 700 m below the present top of the Hrossakambur lava pile, and the minimum water pressure indicated by the absence of tridymite is 200 kg/cm^2, which corresponds to a cover of about 700 m of basalt (Brown, 1963). In addition, the position of the rock on Fig. 95 indicates that it would plot either on the quartz-feldspar boundary curve or just inside the quartz field at pressures of the order indicated by the field relations and mineralogy of the vein.

Carmichael (1963b, p. 124) has suggested that "acid rocks whose salic normative compositions (less anorthite) fall clearly in the quartz field (Wager et al., 1953), of the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2 must also be products of fusion, as no liquid higher up a fractionation sequence contains a higher proportion of quartz to feldspar than rhyolite or felsite itself". Thus the chemical evidence obtained appears to confirm the palingenic origin of the Type 2 acid veins.

The dacite and pitchstone (13 and 14) plot close to the quartz - feldspar boundary at 500 kg/cm^2; no quartz phenocrysts were found in either rock, and their field relations indicate that they crystallized at a similar crustal level to that of the acid vein (9), the pitchstone (14) lying at a slightly lower level than the dacite (13). These two rocks are thus taken to have crystallized within the albite field at low water-vapour pressures.

5-3. COMPARISON OF THE CHEMISTRY OF THE FIRST AND SECOND PHASE ROCKS.

The variation diagrams (Figs. 91-94) and the norms (Table 20) reveal distinct differences in the chemistry of the First and Second Phase rocks analysed, and these differences, most noticeable in the basic rocks, are as follows:-

First Phase	Second Phase
Plots follow Skaergaard trend on albite ratio - iron ratio diagram (Fig. 94).	Plots follow Thingmúli trend on albite ratio - iron ratio diagram.
Normative feldspar low in orthoclase (Fig. 93).	Normative feldspar relatively high in orthoclase.
FeO/Fe_2O_3 ratio low in basic rocks. (1.18 - 1.44), Table 19.	FeO/Fe_2O_3 ratio high in basic rocks. (2.63 - 4.06).
Hypersthene low relative to diopside in norm or even absent (see Table 20).	Hypersthene high relative to diopside in norm, and quartz may be present.

The apparently low oxidation state of the Second Phase basic rocks is thought to be due to their relatively young age and absence of hydrothermal alteration compared to the First Phase basic rocks.

5-4. PETROGENESIS OF THE VIDIDALUR-VATNSDALUR ROCKS.

The balance of evidence indicates that the intrusive rocks of the Vididalur-Vatnsdalur area were emplaced in two temporally separated phases of short duration and contrasted mineralogy and chemistry; the separate intrusions of each Phase were emplaced in rapid succession, the occurrence of basic-acid composite bodies indicating that basic and acid material sometimes were simultaneously available for injection into the country rock lava pile.

It is often difficult to find unequivocal evidence of the affinities of the Vididalur-Vatnsdalur intrusive rocks from their field relationships, as many of them form small isolated and apparently disconnected intrusions; however, the close association of the intrusions of each Phase within a relatively small area and a short time period suggests that they have a closely related origin, and this is further indicated by the field petrographic and chemical similarities intrinsic to the products of each of the two Phases.

The chemistry of the analysed rocks shows similarity to that of the Thingmúli and Skaergaard tholeiitic series, which are considered to be the result of continuous fractionation of basic tholeiite magma (Wager and Deer, 1939; Wager and Brown, 1968; Carmichael, 1964); the rocks analysed follow the iron-enriched Thingmúli trend on a FMA plot (Fig. 91) and are all richer in soda than potash (see Table 21, Fig. 95). The greater proportion of soda relative to potash in the acid rocks of Thingmúli and Slaufrudal has been attributed to their development by fractionation of basic tholeiite magma, and the relative soda enrichment in the Vididalur-Vatnsdalur acid rocks may have a similar origin.

Coarse-grained intrusive rocks of intermediate composition are rare in the area studied, and the largest bodies of intermediate rock found are of hybrid origin. Nockolds (1936) drew attention to the rarity of intermediate magmas in basic-acid igneous associations and suggested that perhaps the pyroxene and plagioclase crystallized through a comparatively small temperature range, so that intermediate rocks would not form unless the residual magma was removed during a comparatively short space of time. It was suggested by Bowen (1928, p. 91) that intermediate plagioclase would be largely confined to the outermost zones of primocrysts.

1. THE SYSTEM DIOPSIDE-ANORTHITE-ALBITE AND THE DIFFERENTIATION OF BASALTIC MAGMA.

This system was first investigated by Bowen (1915) and his equilibrium diagram is shown in Fig. 96. The normative diopside, anorthite and albite (recalculated to 100 per cent) of the rocks analysed are plotted on this diagram, using the data of Table 23.

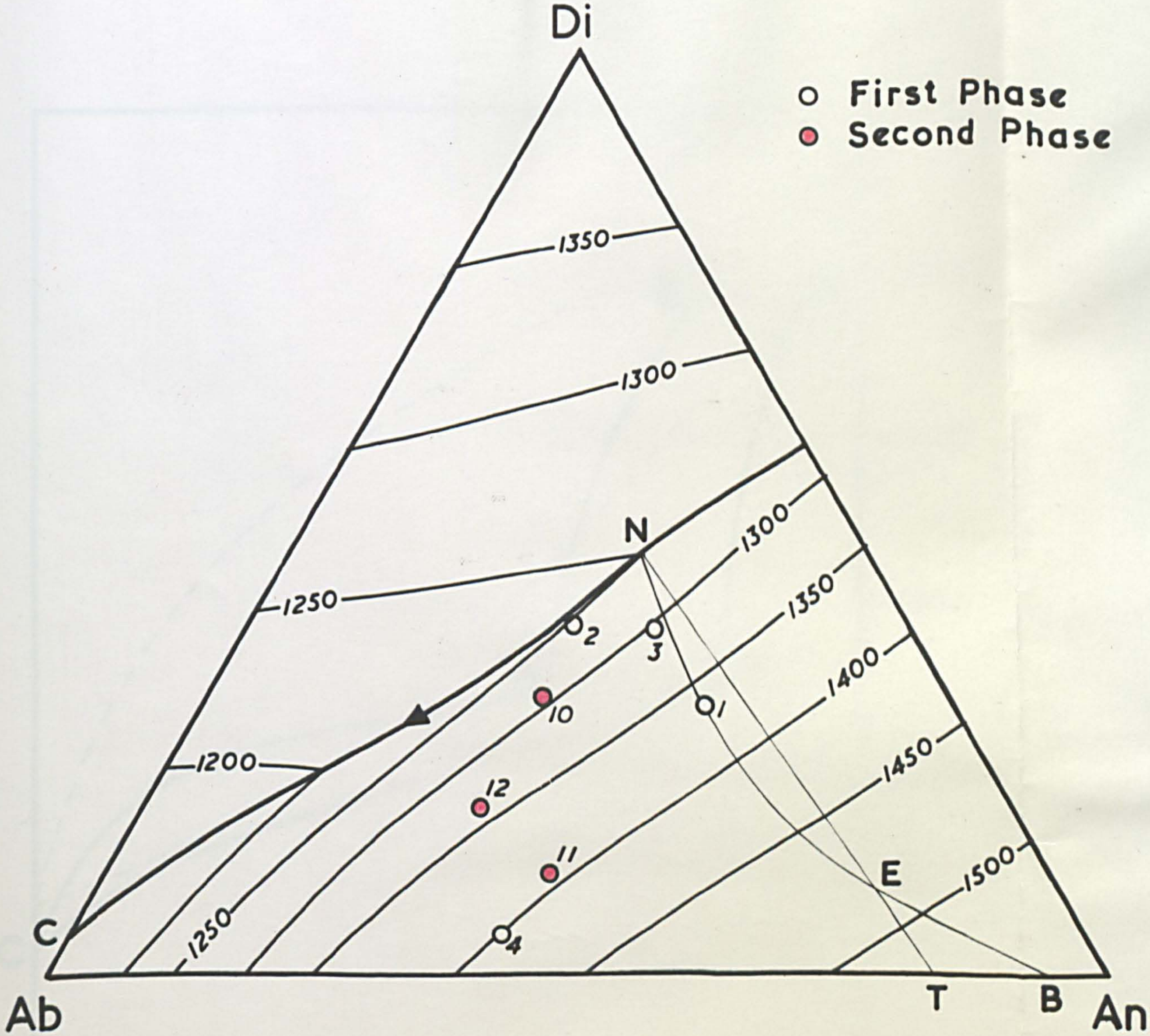


Fig. 96. The system diopside-anorthite-albite after Bowen (1915); the crystallization course is taken from Wyllie (1963, Fig. 2A), and the points for the Vididalur-Vatnsdalur basic and intermediate rocks are plotted from the data of Table 23.

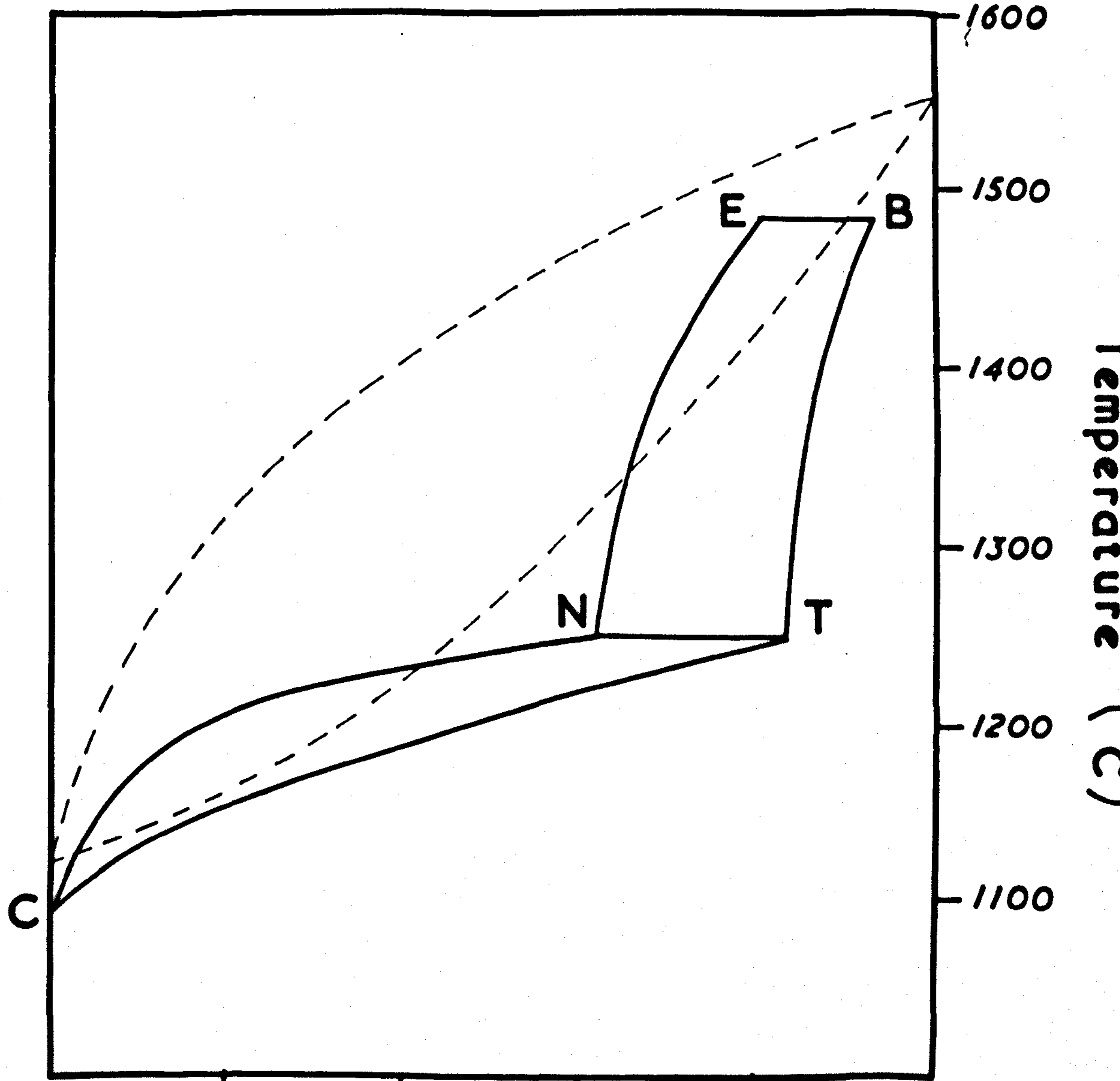


Fig. 97. A section through the system diopside-anorthite-albite, showing the projection of the diopside-plagioclase field boundary and the solidus on to the An-Ab-T face of the prism (from Wyllie, 1963, Fig. 2C); the liquidus and solidus boundaries for the system anorthite-albite (Bowen, 1913) are also shown.

Table 23.

NORMATIVE DIOPSIDE-ANORTHITE AND ALBITE OF THE VIDIDALUR-VATNSDALUR ROCKS PLOTTED IN FIG. 96.

Number on Fig. 96.	Rock type	Normative per cent (Weight)			Total	Recalculated to 100 per cent		
		Di	An	Ab	(Di+An+Ab)	Di	An	Ab
1	Main facies eucrite, Hólar.	25.06	39.78	20.01*	84.85	29.53	46.88	23.59
3	Lower marginal dolerite, Hólar.	28.15	22.66	23.83	74.64	37.71	30.37	31.92
11	Olivine-free tholeiite, Hjallin.	20.69	21.46	26.61	68.76	30.09	31.22	38.69
2	Pegmatitic gabbro, Urdarfell.	25.50	26.04	16.92*	68.46	37.25	38.03	24.72
12	Olivine-free tholeiite, Gálgagil.	11.29	19.82	31.44	62.55	18.05	31.69	50.26
10	Olivine-tholeiite, Sandfell.	5.88	22.04	25.00	52.92	11.11	41.65	47.24
4	H_I hybrid, Urdarfell.	2.12	19.81	26.83	48.76	4.35	40.63	55.02

*Corrected for normative nepheline.

Wyllie (1963) considered the crystallization of basic magmas with reference to the system diopside-anorthite-albite and showed that this ternary system gives a fairly realistic picture of the crystallization of very simple basaltic liquids: "Each liquid on the field boundary coexists with diopside and a plagioclase feldspar of fixed composition, and the three phases coexisting at each temperature are represented by the corners of a three-phase triangle...During crystallization, the liquid and the plagioclase feldspar are enriched in albite relative to anorthite. The extent of this enrichment is indicated by the ratio of albite/anorthite (Ab/An)". Wyllie (op. cit., p. 205-206). Wyllie points out that the slopes of the liquidus and solidus paths for plagioclase in the ternary system differ from those of the corresponding liquidus and solidus paths in the binary system in the manner shown in Fig. 97, which represents a section through the system diopside-anorthite-albite at atmospheric pressure and is taken from Wyllie (op. cit., Fig. 2). This figure shows the projection of the diopside-plagioclase field boundary and the solidus from within the TX prism on to the An-Ab-T face of the prism, and the liquidus and solidus boundaries for the system anorthite-albite (Bowen, 1913) are also shown; as Wyllie points out (op. cit., p. 206); "Ternary crystallization temperatures are lower and, except near albite, the projected ternary field boundary and the solidus both slope much more gently than in the binary system. The difference in composition between coexisting liquid and plagioclase in terms of the ratio Ab/An is smaller in the ternary than in the binary system. This is also true for plagioclase precipitated from multicomponent magmatic liquids (Wager, 1960, Fig. 12)".

Wyllie shows that when plagioclase crystallizes alone from the ternary system, both liquidus and solidus paths are steeper than in the anorthite-albite system; when plagioclase is joined by diopside, both paths become much less steep than in the binary system (see Fig. 97) and thus the field boundary will generate a surface of shelf form. It will be seen from Fig. 97 that little differentiation will occur while plagioclase is the only mineral crystallizing from a multicomponent liquid, despite the large temperature drop. The gentle slopes (i.e. the shelf) of the lower-temperature part of the curves "indicate that when plagioclase is joined by other crystalline phases much differentiation occurs in a small temperature interval" (Wyllie, op. cit. p. 206).

Fractional crystallization in this system, with continuous zoning of the plagioclase will lower the temperature of final consolidation, and will enrich the liquid and the outermost plagioclase zones in the ratio Ab/An. "The final liquid persists to much lower temperatures than indicated by..OL (see Fig. 97) and with strong fractionation the late liquids, and the outer plagioclase zones, could continue to the point C, the albite-diopside eutectic.." (Wyllie, op. cit., p. 206).

The effect of pressure on this system is not known in detail (Wyllie, 1963), but the melting temperature of plagioclase is known to be greatly lowered by water pressures of a few thousand bars (Turner and Verhoogen, 1960, p. 102 and Fig. 5b).

2. APPLICATION OF THE SYSTEM DIOPSIDE-ANORTHITE-ALBITE TO THE CRYSTALLIZATION OF THE VIDIDALUR-VATNSDALUR BASIC ROCKS.

As a result of his consideration of the system diopside-anorthite-albite, Wyllie produces a "tentative working model representing one possible liquidus path through the multicomponent system including all igneous rocks" (op. cit., p. 209) and this is shown in Fig. 98; the liquidus profile in this model shows the "rate of change of liquid composition for a constant rate of temperature change during the fractional crystallization of a magma, or the fusion of a crystalline igneous rock" (op. cit., p. 208). It will be seen from Fig. 98 that three shelves are present; in the interpretation of the Vididalur-Vatnsdalur rocks only the middle and lower shelves are considered. The middle shelf is broadly analogous to the shelf already described in the diopside-anorthite-albite system (Fig. 97) and a small drop in temperature in a liquid moving down this part of the liquidus will result in rapid zoning of the minerals being precipitated from the liquid. In small to moderate-size

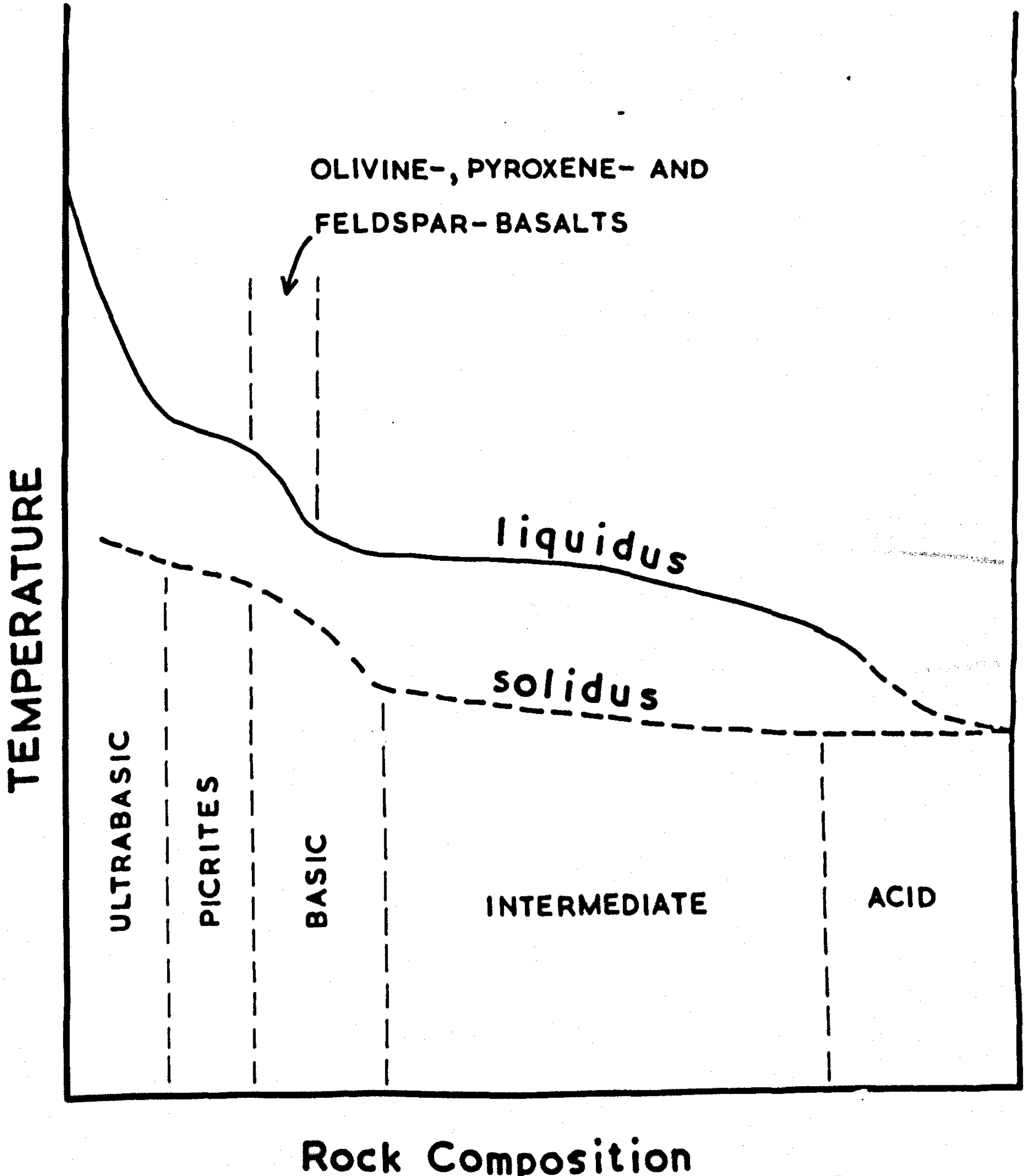


Fig. 98. "Possible liquidus and solidus paths for an igneous rock series. The liquidus profile represents one liquidus path through multicomponent space. The solidus profile does not represent a solidus path for any particular mineral. This tentative diagram illustrates schematically the temperatures of beginning of melting and of complete melting for a series of igneous rocks". (from Wyllie, 1963, Fig.4).

intrusions, the rapid rate of cooling would carry the liquid rapidly across the middle shelf so that rocks bearing highly zoned crystals of intermediate compositions (labradorite-andesine plagioclase, fayalitic olivine, etc.) would be formed. This is the same result of fractional crystallization as that originally envisaged by Bowen (1928, p. 91), the primocrysts bearing outer zones which correspond <u>in toto</u> to rocks of intermediate composition. Most of the basic rocks of the First and Second Phases bear small patches of late-stage salic residuum, usually of glassy or micrographic character, and their highly fractionated nature is shown by the wide zoning ranges in their plagioclase and olivine; this character is felt to be due to rapid cooling across the shelf (Figs. 97 and 98) after the partially crystallized tholeiite magma was rushed upwards into cooler, lower-pressure crustal levels. The rapid cooling is evidenced by the mineralogy of the rocks, which bear high-temperature (disordered) sodic plagioclase as groundmass crystals and phenocryst rims, pigeonitic groundmass pyroxenes and very immature exsolution textures in their calcium-rich clinopyroxenes: the fine grained marginal facies of the Hólar-Skessusaeti eucrite and the First and Second Phase cone-sheets, and the frequent development of thin tachylitic selvages and abundant interstitial glass by these sheets are further evidence of their rapid final cooling.

Wyllie's interpretation also explains the apparent existence of two generations of plagioclase and olivine in the Vididalur-Vatnsdalur basic rocks; "crystallization of the magma on the steep slope preceding the shelf produces a few large crystals of fairly uniform composition. When the plagioclase is joined by diopside (which can be regarded as representing the other minerals precipitated from the magma) crystallization on the shelf causes precipitation of many smaller plagioclase crystals, in addition to the marginal zones formed around the existing large crystals", (op. cit., p. 210). No compositional break was found in the plagioclase crystals of the basic rocks studied and it is emphasized here that the grouping into phenocrysts, microphenocrysts and groundmass crystals in the Vididalur-Vatnsdalur rocks is made solely on the basis of size of the individual crystals. The textures of these basic rocks also indicate that the precipitation of the numerous smaller plagioclase crystals approximately coincided with the start of groundmass clino-pyroxene crystallization; this is evidenced by the enclosure of groundmass pyroxene grains by labradorite rims to phenocrysts and the poikilophitic intergrowths of plagioclase laths and groundmass augite grains.

The pattern of plagioclase crystallization in the Vididalur-Vatnsdalur basic rocks is, however, not quite so simple as it would appear from Wyllie's hypothesis. Some of the large bytownite-anorthite crystals in the cone-sheets of each Phase are believed to be of intratelluric crystallization, as they occur in small clusters in which they are intergrown with occasional augite and olivine in textures identical to that of the eucrites; these crystals usually show a very limited range of continuous zoning in the range An_{90-80}, and more sodic plagioclase appears to be developed only at the rims of the more loosely-packed crystals on the edge of the eucritic clusters. It is thus felt that these clusters represent primocrysts which began crystallization at depth in a site of plagioclase accumulation and were entrained by the ascending cone-sheet material; those crystals in the centres of the partly consolidated eucritic cumulate clusters were insulated from the host liquid by the more peripheral crystals, which became zoned and sometimes broke away to exist as single xenocrysts. Field relations indicate that the First Phase cone-sheet material is approximately coeval with that of the eucrites, and the textural and mineralogical similarities of the sheets and the Hólar-Skessusaeti chilled marginal eucrite reinforce this evidence; the eucrite, however, bears olivine phenocrysts in all its modifications and is therefore thought to be an olivine-bytownite cumulate facies from a deeper level of the accumulation site than that from which the cone-sheets proceeded, as early-formed olivine phenocrysts show a marked tendency to sink towards and concentrate in the lower levels of other large bodies of eucritic liquid such as those of Rhum (Wadsworth, 1961). By analogy with the more extensively-exposed Vesturhorn intrusions of eastern Iceland which show some development of olivine-cumulates (Cargill et al., 1928, pp. 514-15; J. Roobol, pers. comm., 1967), it seems likely that the relatively small Hólar-Skessusaeti eucrite intrusion passes downwards into a larger more olivine-rich body.

The history of plagioclase crystallization in the Second Phase cone-sheets and eucrites is broadly similar to that seen in the First Phase rocks; in these later intrusions the occurrence of a composite basic cone-sheet with a later-emplaced central part of olivine-eucrite flanked by fine-grained Type 1 olivine-tholeiite of similar mineralogy bearing eucritic clusters appears to indicate that the two rock types are cogenetic, the eucrite being a cumulate variant of the Type 1 material (see p.255).

The occurrence of occasional gabbroic labradorite clusters in the First Phase cone-sheets probably indicates that a large body of fractionating basic material lay beneath the area at this time; no single labradorite phenocrysts were found in these sheets. These labradorite crystals were found to have high-temperature optics, which indicates that they were precipitated under essentially volcanic conditions. Like the bytownite crystals in the eucrite cumulates, these labradorites were found to be virtually unzoned and to be intergrown with augite; these gabbroic clusters also contain some ore, unlike the eucritic clusters and they are thus believed to be part of a later fraction of the original eucrite liquid. Similar gabbros bearing high-temperature labradorite were found as small intrusions of First Phase age at Steinsvad and Urdarfell, and the analysed Urdarfell gabbro is a labradorite cumulate (see p.407) high in normative and modal clinopyroxene. The general appearance and mineralogy of this rock is similar to that of the pyroxene-rich "wavy-pyroxene rock" of the Skaergaard Tranquil Group, which is believed to represent a liquid supersaturated with respect to pyroxene (see p.404); the analysed Urdarfell rock (2) bears higher modal clinopyroxene (34.8 per cent by volume) and higher normative diopside (28.15 per cent weight) than any of the other analysed rocks in the First Phase eucrite-gabbro series (see Fig. 95 and Table 23) and this is taken to suggest that it too crystallized from a liquid extremely rich in pyroxene. The occurrence of an identical rock as "pools" and streaks in the margins of the Hólar-Skessusaeti intrusion and as the latest-injected component of a composite vein (see p.122 and Fig. 16) is felt to indicate that this pyroxenic gabbro is a late-stage fraction of the eucrite liquid, and this is further suggested by the slightly higher iron content of its augite relative to that of the eucrite (cf. Nos. 1 and 5, Table 11). The Urdarfell gabbro shows slightly undersaturated character, bearing normative nepheline and olivine in similar fashion to the Hólar-Skessusaeti eucrite (see Table 20), and this is also believed to evidence its affinity to the eucrite. The Steinsvad gabbro augite shows similar composition to that of the analysed gabbro (2) (see Table 11, No. 7) and this rock is also interpreted as a later fraction of the eucrite liquid.

"Pegmatitic" gabbros rich in augite have been described from similar environments in the Hornafjördur area by Annels (1967) who shows that these rocks have a low feldspar content due to their high pyroxene content, and the Urdarfell rock is comparable to these rocks, having a silica content of only 41.70 (see Table 19) which displaces it considerably from the Thingmúli and Skaergaard trends on the $FeO+Fe_2O_3/FeO+Fe_2O_3+MgO$ versus SiO_2 plot (see Fig. 92). The lower marginal dolerite (3) of the Hólar-Skessusaeti intrusion may represent a later derivative of the eucrite cone-sheet liquid of similar fractionation stage to but earlier injection than the Urdarfell gabbro; the dolerite lies a little farther along the fractionation trends than the gabbro (see Figs. 91-95) and its apparent "anticipation" of the order of intrusion relative to the gabbro is possibly due to its more rapid cooling across the shelf (Fig. 98) and hence more rapid fractionation, as evidenced by its fine grain. These two rock types thus appear to be the products of liquids which split off from the main magma body.

The three components of the Hólar-Skessusaeti intrusion have been discussed at some length as they are the only First Phase bodies to show demonstrably close physical association in the field; in addition, the members of this small group show broadly serial mineralogical and chemical features which suggest that they are related products of the same eucritic liquid.

3. INTERMEDIATE ROCKS. General considerations.

There are few processes by which separate bodies of intermediate liquid could have been derived under a high level regime such as that indicated by the high-temperature plagioclase phenocrysts in the Vididalur-Vatnsdalur rocks. During the relatively rapid cooling indicated by the petrography of these rocks, the intermediate fractions of the basic liquid would be formed as the outermost zones of already-precipitated crystals in the manner suggested by Bowen (1928) and Wyllie (1963); this is indicated by the strong zoning of the plagioclases in these basic rocks (see Chart 2).

The physical difficulties involved in concentrating intermediate and acid liquids have been pointed out by Holmes (1936) and will be mentioned later; some concentration of the intermediate liquid fractions and their precipitates could occur in a convection system within a magma reservoir such as that of the Skaergaard intrusion (Wager and Deer, 1939; Wager and Brown, 1968). The present meagre evidence of small apophysis outcrops and a few cumulate xenoliths does not allow detailed consideration of the nature of the differentiation site from which the Vididalur-Vatnsdalur rocks evolved; however, the sequence of emplacement of the First Phase basic to intermediate rock types (Fig. 37) suggests that a large body of fractionating basic magma was situated at some depth below the Vididalur-Vatnsdalur area and was tapped at time intervals which represent consecutive stages in a fractionation sequence.

Specific considerations.

The Hólar schliere (p.312 and Fig. 56) is a rock of approximately intermediate composition which shows marked textural and mineralogical similarities to the marginal facies of the Urdarfell diorite, being an orthocumulate of tightly-packed euhedral plagioclase crystals zoned continuously from cores of An_{50} to rims of An_{36} in company with a few euhedral augite prisms, and some apatite and ore phenocrysts; all these crystals are set in a fine grained felsitic matrix and they show no obvious signs of corrosion. The marginal diorite (p.376 and Fig. 70) bears plagioclase phenocrysts zoned continuously from cores of An_{53} to rims of about An_{20}, and also has a felsitic matrix.

The composition of the feldspar phenocrysts in these two rocks is such that the crystals could have been precipitated from the later fractions of a basic liquid such as that of the gabbro or the marginal dolerite, but the presence of the abundant acid matrix is more difficult to explain. It is possible that this acid material represents the final residuum of a tholeiitic liquid, by analogy with the similar material commonly found in the final mesh gaps of the other First Phase basic rocks, but its abundance in the schliere presents a further interpretative difficulty. Holmes (1936, p. 231), in reference to the high proportion of acid interstitial material in the intermediate portions of the

Glen More ring dyke of Mull, has pointed out that concentration of such residual material "would be mechanically impossible" in a "liquid-filled meshwork of closely interlocking crystals". Holmes further states (loc. cit.): "Separation of the acid residuum by squeezing, due to the application of externally applied stresses, could be brought about only by intense deformation of the crystal meshwork. The necessity of this condition is clearly recognized by Eskola when he refers to acid interstitial magma 'which can be squeezed out if the rock is powerfully rolled out'".

The Glen More ring-dyke was emplaced in a non-orogenic region broadly similar to Iceland and Holmes' remarks are thus felt to be especially relevant to the present problem. The largest-scale evidence of crustal movements observed in the northern part of Vididalsfjall and contemporary with the emplacement of the hybrids is limited to normal faults of relatively small throw which probably could not exert a powerful enough squeezing effect on a largely consolidated gabbroic body (such as that in which the plagioclase and pyroxene crystals originated) to cause local concentration of the acid residuum in sufficient volume to form the Urdarfell diorite body.

An alternative explanation of the origin of the schliere and the diorite is indicated by the petrography of these rocks (see pp.312 and 376) and it seems likely that they are hybrids which formed by mechanical mixing of an intermediate plagioclase cumulate and already existing acid material; little reaction between plagioclase and pyroxene crystals and the acid matrix was seen in the fine-grained schliere and the marginal diorite, possibly due to the rapid cooling of these types, but the margins of the plagioclases and pyroxenes in the coarse-grained main facies diorite were often seen to be corroded by the surrounding acid granophyric matrix (see p.381-82). The hybrid appearance of the Urdarfell diorite types has already been pointed out (p.388). This hybrid origin would explain the apparent excess of acid material in these intermediate rocks, and would remove the necessity of invoking rather dubious mechanical methods of concentrating this material in a basic intrusion. The field relations of the First Phase intrusions indicate that the lower marginal dolerite of the Hólar-Skessusaeti intrusion was emplaced at broadly the same time as the Dalsá-Urdarfell felsite (see Fig. 37) and this would have been at about the same stage as that at which the more sodic plagioclases were precipitated from the main body of basic material undergoing fractionation beneath Vididalsfjall. With this evidence of simultaneous availability of basic-intermediate and acid material in the central zone, it seems possible that the two types could have commingled to form the dioritic material which was later intruded as a body of separate identity to form the Urdarfell H_I,H_F and H_G hybrid rocks; this interpretation is thought to be the most likely explanation of the origin of the Hólar schliere and the Urdarfell diorite.

4. ACID ROCKS.

The present stage of knowledge of the Vididalur-Vatnsdalur acid rocks offers no new evidence regarding the origin of Icelandic acid material; the intrusions studied are small and only their upper parts are exposed. The analysed acid rocks (see Tables 19 and 21 and Fig. 95) contain high soda relative to potash, as do the acid rocks of the Skaergaard intrusion (Wager and Brown, 1968), Thingmúli (Carmichael, 1964), and Slaufrudal (Beswick, 1965), all of which are believed to have formed by fractionation of basic tholeiitic material.

An origin by fusion of sialic material seems difficult to substantiate in Iceland, as Carmichael (1964, p. 456) has pointed out that this material would have to fuse to a liquid relatively poor in silica and with soda exceeding potash in order to produce the one-feldspar (plagioclase to anorthoclase) acid rocks typical of Iceland. Sigurdsson (1967b, p. 42) has suggested that a young sialic crust might have been formed beneath Iceland, and he cites as evidence strontium-isotope work by Moorbath and Walker (1965) whose results can be interpreted in two ways; either (a) the basic and acid magma are closely related (the latter having arisen by differentiation of the basic magma), or (b) the acid rocks may have been derived by assimilation, the sialic source being very young (less than 100 m.y. old) or having an abnormal strontium-ratio. More recent work by Welke et al., (1968), (Dr. S. Moorbath, pers. comm., 1968) on the lead isotope ratios of a broad range of Icelandic igneous rocks indicates that the igneous rocks of Iceland originated in an essentially homogeneous 4530 ± 20 m.y. mantle system and were separated from this system in upper Tertiary times (op. cit., p. 220). The lead isotope ratios of these rocks are also "inconsistent with derivation from or contamination with ancient sialic material" (op. cit., p.230).

The volume of acid material in the Vididalur-Vatnsdalur area (and near other volcanoes) appears to be greater than that which could be formed by simple fractionation of tholeiite, and it is difficult to ignore Holmes' (1931) objections to the formation of acid rocks in this manner and his apparently realistic hypothesis of the formation of acid rocks by remelting of sialic material. One of the weakest points in the theory of a tholeiite fractionation origin for large bodies of acid material is that it is difficult to envisage a convincing mechanism for concentration of the acid material if this exists as a residual liquid; the impracticability of squeezing the residual acid material from a largely consolidated gabbroic crystal mesh has already been mentioned (p.584-85; Holmes, 1936, p. 231). If therefore, it is difficult to concentrate this acid material, it is also difficult to explain the simultaneous availability of basic and acid material observed in the area studied and in other parts of Iceland; the First Phase Gálgagil tuffs were found to contain separate euhedral single crystals of uncorroded bytownite and andesine within the same thin section (see p.477-78) and the large size of these crystals is felt to suggest that discrete bodies of basic and acid material existed beneath the volcano prior to the explosive eruption during which they were rapidly mixed.

The recent discovery of acid plutonic xenoliths in the lavas of the new volcanic island Surtsey and in a number of small volcanic vents in southwestern Iceland has lent further support to the hypothesis that sialic material exists at depth beneath Iceland (Sigurdsson, 1966b, 1968).

Evidence of the remelting of acid bodies intruded by later basic bodies has been found on southwestern Urdarfell in the form of thin acid veins (p.412), and the black glass produced by fusion of the acid tuff on which the Hjallin lens lies is another example of this phenomenon; Carmichael (1964) has noted the occurrence of acid tuffs cut and fused by basic dykes at Thingmúli. The presence of such recycled material near the relatively small parts of the basic intrusions exposed in the Vididalur-Vatnsdalur area may indicate that larger volumes of remelted acid material are present in depth where the basic intrusions are thought to increase in size and to represent more potent sources of heat.

5. POSSIBLE EVIDENCE FOR CONTAMINATION AND ASSIMILATION.

The Vididalur-Vatnsdalur intrusive suite is a very varied assemblage of rock types, and there is some evidence that the Second Phase intrusions have encountered First Phase material during the ascent to their present position; the Skessusaeti L_E composite cone-sheet was found to bear a small xenolith of material very similar in appearance to the First Phase intermediate hybrid rocks, and this small inclusion shows indistinct margins which are felt to be suggestive of incipient remelting and assimilation of its acid matrix by the enclosing eucrite (see p.428). The thin Type 2 veins of fresh leucocratic granitic material on southwestern Urdarfell are also believed to be the result of remelting of First Phase acid rocks by hidden Second Phase basic intrusions (p.413). It seems not impossible from this evidence that other similar encounters between Second and First Phase material may have occurred; the First Phase eucrite, gabbro and granophyre exposures are believed to represent offshoots of larger bodies concealed in depth and this would increase the probability of cross-cutting of these intrusions by Second Phase intrusions. Complex cross-cutting relationships between intrusions of different intrusive phases are common in the deeply dissected central complexes of Mull, Ardnamurchan, Skye and other regions within the Hebridean Tertiary Province, and it seems likely that the deeper levels of the area studied may resemble these complexes in structure.

The possibility of other intrusive complexes and volcanoes being concealed at depth is indicated by the presence of basic, hybrid and acid rocks as small ejected blocks in the

Gilá tuff, which lies at a similar stratigraphic level to the Gálgagil tuff (see Chart 1). Walker (1966a, Fig. 4) has shown that twelve near-consecutive periods of central volcanic activity are known to have occurred in the time interval between the base and top of the eastern Iceland lava pile, and, by analogy, the Vididalur-Vatnsdalur volcano may represent a single member of such a series in northern Iceland.

Because of the spatial proximity of the intrusions studied it seems possible that the later basic intrusions might remelt and assimilate earlier acid material; the relatively high residual glass content of much of the Type 1 Second Phase basic material may be due to the incorporation of small quantities of earlier acid material prior to the main period of crystallization of these basic rocks. The presence of occasional small interstitial patches of acid quartzo-feldspathic material in the coarse-grained basic intrusions of Hólar-Skessusaeti, Borgarvirki, Steinsvad, Skessusaeti summit and Hnjúkur may also have a similar explanation; the general principle in operation is believed to be one of rather diluted hybridization broadly similar to the more concentrated process in which the Urdarfell acid-intermediate hybrids were formed from dioritic material encountering a large volume of acid material. The effects of assimilation of small quantities of acid material by basic material could be expected to be more noticeable in small intrusions and the marginal parts of larger intrusions such as are exposed in the Vididalur-Vatnsdalur area.

It is possible that assimilation of small quantities of earlier acid material may be responsible for the noticeably higher potash contents of the analysed Second Phase basic rocks compared to those of the First Phase basic rocks as reflected in their normative feldspars (see Table 19, Fig. 95).

6. ORIGIN OF THE URDARFELL HYBRID ROCKS.

The evidence of the crenulate and lobate forms developed in the Urdarfell diorite at its contact with the MU granophyre (see Fig.32) is taken to indicate that the denser, more basic material was intruded into the acid material while this was still plastic; this plasticity is thought to have been largely due to the high temperature of the newly emplaced and partly consolidated granophyre magma but it is possible that the diorite produced a small local heating effect. The balance of evidence appears to suggest that the H_I and H_G rocks were formed by mechanical mixing of the diorite and the mobile MU granophyre in the manner observed in the diffuse small lobate structures in the contact zone (see Fig. 32); the textures of the marginal facies indicate that the diorite was in the form of a closely packed but incompletely consolidated cumulate of plagioclase, augite, apatite and ore crystals suspended in an acid liquid. The form of the upper part of this mass appears to have been approximately wedge-shaped and the upper edge intruded the overlying Urdarfell felsite, remelting part of this rock and mixing with it to form the fine-grained H_F hybrids. By this time, the upper part of the inner diorite had begun consolidation and this was back-veined by the H_F rock.

In the steeply inclined hybrid zones of the fault gully (see Fig. 33, section NP), the proportions of the plagioclase, augite, ore and apatite crystals decrease towards the base of the gully wall, the colour index of the rocks gradually decreasing until the lowest exposed rock is a pale H_G granitic rock showing only slight enrichment in ferromagnesian minerals relative to the normal MU granophyre. This downward decrease in the proportions of xenocrysts is illustrated in Table 24 by the modes of the H_I and H_G rocks and is believed to have resulted by crystal sinking under the influence of gravity during and after their rolling into the underlying acid material by the effect of flow friction on the lower edge of the diorite wedge.

<u>Table 24.</u>

PARTIAL MODES (PER CENT BY VOLUME) OF THE HYBRID ROCKS.

	Diorite	H_I	H_G
Plagioclase	49.1	38.6	7.2
Clinopyroxene	16.3	7.5	c.3.9
Ore	3.1	4.3	2.3
Graphic quartz-feldspar material	29.2	48.2	-

This mixing by a rolling effect is believed to have operated prior to and during intrusion and the formation of hybrids by mechanical mixing of intermediate and acid material is essentially similar to the process suggested by Beswick (1965, pp. 87 and 256), to account for the origin of the Slaufrudal hybrid rocks.

Shaw (1965, p. 123), has suggested that hydrous acid melts probably behave as Newtonian liquids even at temperatures lower than about 100°C below liquidus temperatures, provided that their water content is greater than a "few tenths of a per cent"; he cites generalized experimental evidence to show that the viscosity of stable liquids of ternary minimum composition coexisting with an H-O-rich gas phase could be expected to lie within narrow limits of 10^6 to 10^8 poises if their water content exceeds about 1 per cent by weight (op. cit., p. 121). This viscosity range will allow sinking of intermediate plagioclase (op. cit., p. 128) and it follows that augite, apatite and ore will sink in a granitic liquid, as they are more dense than plagioclase. The petrographic evidence (p. 210) indicates that the MU granophyre originally contained more than 1 per cent by weight of water and thus the evidence presented by Shaw (op. cit.) and the petrographic characters of the Urdarfell hybrid rocks would appear to support the possibility of mechanical mixing of the diorite and granophyre components in the manner suggested.

CONCLUSIONS.

The main conclusions of the present study are summarised briefly as:

1. Two distinct Phases of Upper Tertiary central volcanic activity have been distinguished in the area studied; these are characterized by the development of distinctive basalt, andesite and rhyolite lava flows, and intercalated pyroclastic horizons. The products of the First and Second Central Phases interfinger with the contemporaneous flood basalts; a distinctive Flood Phase separates these two central volcanic episodes.

2. The fracture pattern in the lava pile is of dominantly north to north-northeast trend, most of these fractures being normal faults of small vertical displacement. One west-northwest trending fault which may be a transcurrent fault has been found in southern Vatnsdalur. There is evidence that movement occurred along many of the northerly fractures throughout the time interval represented by the exposed rocks; in the Hjallaland-Hvammur region such movement, possibly combined with withdrawal of magma at depth, caused the formation of an asymmetrical subsidence trough.

3. The basic dyke swarm in the area has a north to north-northeast trend; these dykes are very thin and are of a range of petrographic types which suggests that they were emplaced continuously throughout the period of lava

3/. extrusion. The densest part of the swarm passes east of the main Vididalsfjall intrusive centre and the swarm density decreases towards the top of the lava pile. One BFB dyke in southern Vatnsdalur appears to have been the feeder to a group of BFB flows.

4. An intrusive centre underlies northern Vididalsfjall where two distinctive and consecutive phases of intrusive activity have taken place; the products of these First and Second intrusive Phases show some differences in petrography and mineralogy, the fresh unaltered condition of the Second Phase intrusions contrasting with the hydrothermally altered state of the First Phase rocks. Each of these Phases began with the emplacement of coarse-grained bytownite cumulates and the injection of basic tholeiitic cone-sheets centred on a focus beneath the Gálgagil-Urdarfell vent zone. The coarse-grained basic and acid intrusions are seen as small outcrops which are probably the upper apophyses of larger intrusions concealed at depth. Coarse-grained intrusions are more abundant among the First Phase rocks than among the Second Phase types due to the deeper erosion level of the older rocks. Rocks of intermediate composition are rare, and occur only in small quantities in the First Phase suite.

5. The early set (First Phase) cone-sheet focus lies about 5 km below sea level whereas the intrusive focus moved upwards to a depth of about 2 km in the case of the late

5/-. set (Second Phase) cone-sheets. These sheets have been intruded along what appear to be concentric spiral cone-fractures. Similar inclined sheet swarms of lesser intensity than that of the Vididalsfjall swarm are centred on Hvammur and northern Svinadalsfjall.

6. Some synchronization between the intrusive and extrusive activity is apparent. The First Phase intrusions appear to have reached their present level during the Flood Phase which succeeded the First Central Phase; the higher-level Second Phase intrusions show considerable petrographic similarity to the Second Central Phase lavas and appear to have been emplaced during extrusion of these flows. One of the Second Phase intrusions (the Hnjúkur plug) shows marked petrographic similarity to the locally developed TFB flow group and may be the feeder to these flows.

7. Hydrothermal alteration of country rock and the First Phase intrusions is most intense near inferred vents in the northern part of the Vididalsá, the Gálgagil-Urdarfell zone, the northern part of the Gljúfurá, the Breidabólsstadur-Hnjúkur zone and the Kornsá-Hvammur ground; major and minor intrusions are concentrated in these parts of the epidote zone, which appear to represent the core zone of the large Vididalur-Vatnsdalur central volcano.

8. Evidence of the simultaneous availability of both basic and acid material has been found in several parts of the area in the form of composite or hybrid intrusions;

8/. mechanical mixing of simultaneously mobile dioritic hybrid rock and granophyre during the First Phase resulted in the formation of small amounts of distinctive intermediate to acid hybrid rocks on Urdarfell.

9. All the intrusive rocks studied are tholeiitic assemblages of plagioclase diopside-hedenbergite pyroxene and iron-titanium oxide with or without olivine, sodic alkali feldspar and quartz; the plagioclases and pyroxenes grade from calcic and magnesian types in the basic rocks to sodic (anorthoclasic) and ferrian types in the acid rocks of the intrusive series. The most basic rocks of each Phase are olivine-tholeiites, but olivine is more abundant in the Second Phase rocks than in those of the First Phase. Phenocrysts of quartz, hornblende, and orthopyroxene occur in some of the fine-grained acid rocks; phenocrysts of quartz and sodic pyroxene, and interstitial sodic amphibole occur in parts of the latest granophyre intrusion.

10. All the intrusions studied show textural and mineralogical evidence of rapid final cooling at high crustal levels. Disordered plagioclase is common in the groundmass and as phenocryst rims in the basic rocks; these rocks commonly contain calcium-poor clinopyroxene as a groundmass mineral and the calcium rich clinopyroxenes have immature exsolution textures. The olivines in the Second Phase basic rocks are highly zoned and the coarse- and fine-grained

10/. basic rocks of both Phases are rich in interstitial glass or salic material. Most of the acid rocks also contain disordered plagioclase and many contain tridymite.

11. The intermediate to acid hybrid rocks on Urdarfell formed by mechanical mixing of an intermediate dioritic plagioclase-augite cumulate and granophyre; these admixed cumulate crystals show evidence of disequilibrium in the hybrid rocks and decrease in abundance with increasing acidity of the enclosing rock.

12. The analysed rocks have low combined alkalis, alumina and magnesia, and are relatively rich in iron and titania; as in the other Tertiary tholeiitic rocks of Iceland, soda is present in greater quantity than potash. The analyses lie on the iron-enriched tholeiitic trend of Nockolds and Allen (1956), and the recalculated normative feldspar constituents plot in the plagioclase-anorthoclase field of a ternary feldspar diagram. The close correspondence of the analysed rocks to trends ascribed to fractionation of tholeiitic material suggests that the entire Vididalur-Vatnsdalur series may have evolved by differentiation in a large body of basic magma beneath the area.

13. The occurrence of small quantities of remelted granitic material as thin veins in the area studied gives reason to doubt a tholeiitic fractionation origin for the more silicic granophyric and granitic rocks of the area.

13/. However, the field, mineralogical and chemical characters of the larger intrusions of granophyre and granite offer no direct or unambiguous evidence of the process by which they evolved.

14. The First Phase basic rocks are chemically similar to those of the Skaergaard intrusion; the Second Phase rocks show greater chemical similarity to those of the Thingmúli series, and are richer in ferrous iron and potash than the First Phase rocks.

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A P P E N D I X

Part 1: OPTICAL PROPERTIES AND COMPOSITIONS OF PLAGIOCLASES FROM THE VIDIDALUR-VATNSDALUR ROCKS.

KEY TO TABLES (a)-(f).

* denotes chemically analysed specimen (see Tables 18-20).

(a) FIRST PHASE ROCKS.

Eucrites.

	Vi 505	Fine-grained upper chilled western margin of Hólar eucrite intrusion, 340 m level.
	B 20	Fine-grained upper chilled margin of Skessusaeti eucrite intrusion, eastern side of Skessusaeti, 590 m.
*	Vi 553	Coarse-grained plagiophyric eucrite, from centre of Hólar outcrop.
	B 12a	Eucrite from 315 m level on eastern side of Skessusaeti.
	B 17	Sub-ophitic eucrite from 555 m level on eastern side of Skessusaeti.
	B 11	Dark eucrite from Borgarvirki intrusion, 200 m west of Litla Borg farm.
	Vi 606	Eucrite inclusion from early set Type 1 cone-sheet. Krossdalur stream bed, 420 m.
	Vi 582	Eucrite block in agglomerate, northern Krossdalur stream bed.
	Vi 97	Eucrite inclusion from early set Type 1 cone-sheet, 500 m north of Melrakkadalur farm.
	Vi 313a	Eucrite inclusion from Type 1 early set cone-sheet, 300 m level in west Raudkollur stream gully.

Early Set Cone-sheets (all samples from centre of sheet unless otherwise specified).

Vi 27	Type 1 2 m. sheet, in stream bed of Dalsá north of Melrakkadalur farm.
Vi 60	Type 1 sheet from 610 m level on ridge to south of Urdarfell.
Vi 605	Lower margin of Type 3 20 cm. sheet, 420 m level in Krossdalur stream bed.
Vi 453	Olivine-tholeiite from small plug in stream bed of Gljúfurá.
Vi 609	Type 2 2.1 m sheet from 400 m level in Krossdalur stream.
Vi 156	Type 2 sheet from eastern bank of Vididalsá, opposite Sida.
Vi 348	Type 1 1.2 m sheet from western side of Ásmundarnúpur.
Vi 4	Type 2 1.2 m sheet from northern bank of Vididalsá, 50 m west of Steinsvad road bridge.

Gabbros.

Vi 94	Gabbro inclusion from Type 2 early set cone-sheet, 465 m in Krossdalur stream bed.
B 13	Pegmatitic sub-ophitic gabbro from vein in lower margin of the Skessusaeti intrusion, eastern side of Skessusaeti, 325 m.
B 14	Same rock type and locality as B 13.
Vi 572	Pegmatitic sub-ophitic gabbro from "pool" in lower level of east margin of the Hólar intrusion, 180 m.
Vi 186	Feldspathic, anorthositic, gabbro from small exposure at 500 m on eastern side of Urdarfell.
* Vi 419	Coarse-grained pegmatitic sub-ophitic gabbro from the Urdarfell tongue-shaped body.
Vi 265/1	Sub-ophitic gabbro from northern margin of the tongue-shaped body in the southern Urdarfell fault gully.
Vi 610	Coarse-grained patch in the Urdarfell tongue.
Vi 2	Dark gabbro of medium-coarse grain from stream bed of Vididalsá beneath Steinsvad road bridge.
Vi 575/7a	Dolerite from lower margin of Hólar intrusion, exposed as slab, 8.2 m from northern edge of slab.
* Vi 575/13	Dolerite from same locality as previous specimen, northern edge of slab.
Vi 575/6	Labradorite-andesine orthocumulate schliere from same slab locality as previous two specimens, 7.9 m from northern edge of slab.
Vi 170	Fine-grained dolerite from 8 m intrusive sheet cutting agglomerate at 350 m in Gálgagil stream.

Diorite.

Vi 215	Fine-grained marginal facies of diorite from upper part of intrusion, 340 m on southwestern Urdarfell.
Vi 401	Coarse-grained main facies of diorite from small outcrop at 260 m on southwestern Urdarfell.
Vi 116	Coarse-grained main facies of diorite from small outcrop lying directly above granophyre at 220 m on southwestern Urdarfell. Specimen from 1 m above contact with granophyre.
Vi 399	Dark, fine-grained diorite schliere in main facies of diorite from small outcrop at 250 m on southwestern Urdarfell.

Basic Granophyre Hybrids. (H_I).

* Vi 265/14 Pale-coloured medium-coarse-grained rock bearing prominent large acicular crystals, 4.6 m below lower contact of gabbro tongue in the southern Urdarfell fault gully.

Vi 265/16 Pale grey medium-coarse-grained rock bearing small acicular pyroxene crystals, 8.5 m below lower contact of gabbro tongue in the southern Urdarfell fault gully.

Granitic Hybrids. (H_G).

* Vi 615 Pale grey medium-coarse grained rock with evenly distributed ferromagnesian minerals, 40 m below lower contact of the gabbro tongue in the southern Urdarfell fault gully.

Vi 265/23 Pale grey medium-coarse grained rock with evenly distributed ferromagnesian minerals, 20.2 m below lower contact of the Urdarfell gabbro tongue.

Acid Rocks.

* Va 35 Porphyritic black pitchstone from northern margin of the Breidabólsstadur intrusion, in small stream, 700 m south of Breidabólsstadur farm.

* Vi 178 Porphyritic blue pitchstone from west contact of the 50-degree inclined sheet in stream bed south-east of Raudkollur.

Vi 174 Pale holocrystalline rock of fine grain from centre of same sheet as Vi 178.

Vi 33 White feldsparphyric felsite from summit of Raudkollur, 749 m.

* Vi 39 Grey felsite, from the Dalsá sheet; sample from east bank of Dalsá, 3 m from granophyre contact.

Vi 409c Grey felsite from 350 m in cliff face formed by sheet on the western side of Urdarfell.

G r a n o p h y r e s.

Vi 38	Pale grey miarolitic granophyre of medium-coarse grain from main facies of the outcrop in the Dalsá stream bed 400 m upstream from Melrakkadalur farm.
* Vi 40	Pale grey miarolitic granophyre of medium-coarse grain and poor in ferromagnesian minerals; specimen from main facies of the outcrop in the Dalsá stream bed, 7.5 m from southern contact of the intrusion.
Vi 262	Pale grey miarolitic granophyre similar to Vi 38 and Vi 40, specimen from 245 m on southwestern Urdarfell.
A 9	Pale grey compact spherulitic granophyre from near west contact of intrusion in the Dalsá stream bed.

(b) SECOND PHASE ROCKS.

E u c r i t e.

Vi 95	Dark coarse-grained plagiophyric eucrite from small intrusion on the summit of Skessusaeti (939 m).

(All samples from centres of sheets unless otherwise specified).

L a t e S e t C o n e - s h e e t s a n d R e l a t e d I n t r u s i o n s.

Vi 551b	Eucrite from 12 m. composite Type 2 sheet on eastern side of Skessusaeti at 565 m. (marked L on Map 2).
Vi 85	Eucrite from 2 m. Type 2 sheet in stream bed of Dalsá in Melrakkadalur (marked L on Map 2).
Vi 28	Olivine-tholeiite from 2 m. Type 1 sheet in Dalsá stream bed 800 m north of Melrakkadalur farm.
Vi 304	Olivine-tholeiite from 1.7 m. Type 1 sheet in crags on north side of Ásmundarnúpur.
Vi 320	Olivine-tholeiite from 4.5 Type 1 sheet in crags on north side of Ásmundarnúpur.
Vi 193	Tholeiite with spare olivine from 2.1 m. Type 1 sheet on Sandfell, (777 m.).
Vi 76	Olivine-tholeiite of Type 1 from small plug in Gálgagil at 300 m.
* Sf 2	Olivine-tholeiite from 2 m. Type 1 sheet 70 m south along ridge from Sandfell 1.
* C 1b	Tholeiite of Type 1 from fine-grained basic inclusion in the Gálgagil composite intrusion; specimen from eastern bank of Gálgagil at 360 m.
C 2	Tholeiite of same type from same locality as C 1b.
Hj 200	Fine-grained tholeiite from 60 m above lower contact of the Hjallin body.

G a b b r o s.

Va 33	Coarse-grained gabbro from central portion of the Hnjúkur plug.
Hnj	Olivine-tholeiite from outer dolerite portion of the Hnjúkur plug, 150 m northwest of summit cairn.
Hj	Coarse-grained feldspathic dolerite inclusion from the Hjallin tholeiite body. Scree block.

A c i d R o c k s.

Vi 200	Fine-grained dacite from northern contact of the small Krossdalur acid intrusion (see p. 449).
Vi 201	Dacite from interior of the Krossdalur intrusion, 0.5 m from northern contact.
Vi 172	Dacite from "mottled zone" of the acid centre of the Gálgagil composite intrusion, 8 m east of upper contact in stream bed.
Vi 168	Dacite from same locality as Vi 172.
* A 14	Dacite from upper contact of acid centre of the Gálgagil composite intrusion in stream bed.

(c) BASALT LAVAS.

Va 1	Tholeiite bearing abundant large, bytownite-anorthite phenocrysts from 15 m flow at 400 m in Grjótá stream bed (BFB).
TFB	Tholeiite bearing abundant large tabular labradorite phenocrysts from 7 m flow at 600 m on western side of Jörundarfell.

EXPLANATION OF SYMBOLS USED IN TABLES (a)-(f).

Crystal Type:	p	phenocryst core
	m	crystal margin e.g. pm denotes phenocryst margin. (measurements made on same crystal are bracketed)
	g	groundmass crystal
	x	xenocryst
Twin Law:	Ab	Albite
	Cb	Carlsbad
	Ab-Cb	Albite-Carlsbad
	Ab-Ala	Albite-Ala
	Ala	Ala (Esterel)
	Mb	Manebach
Structural State:	H	high temperature
	L	low temperature
	T	transitional e.g. HT denotes high transitional structural state.

λ, ϕ — polar coordinates of twin axis positions on stereogram, with $+\gamma$ at $\lambda = 0^\circ$ and $\phi = +90^\circ$, and β (centre of stereogram) at $\lambda = 0^\circ$ and $\phi = 0^\circ$.

R.I. — refractive index

OPTICAL PROPERTIES AND COMPOSITIONS OF PLAGIOCLASES FROM THE VIDIDALUR-VATNSDALUR ROCKS.

Table (a) FIRST PHASE BASIC ROCKS.

Rock type locality and specimen no.	Crystal type	Köhler angles			Twin law	R. I.	Structural state	Composition (mol % An)	
		$\alpha\alpha'$	$\beta\beta'$	$\gamma\gamma'$				U-stage	R.I.
Eucrites.									
Vi 505	p	117	122	89	Ab			83	
	p	117	125	90	Ab			86	
	p	117½	120½	93	Ab			85½	
B 20	p	118½	124½	87	Ab			86-87	
	p	70½	177½	109	Cb			80	
	pm	142½	118½	71½	Ab		H	61	
	pm	134	117	80½	Ab		H	68½	
Vi 553	p	69	179	112	Cb			80-85	
	p	117½	126	88	Ab			80-87	
	p	116	123	90	Ab			80-87½	
	p	119½	124½	88	Ab			80-87	
	(p	73	174½	109	Cb			80)	
	(pm	82½	132½	118½	Cb		H	57)	
	(p	70	178	111½	Cb			77-78)	
	(pm	74	138	121½	Cb		H	60)	
Vi 560	p	73	174	107	Cb	$\gamma' = 1.580$		87-90	90
						$\alpha' = 1.555$			51

OPTICAL PROPERTIES AND COMPOSITIONS OF PLAGIOCLASES FROM THE VIDIDALUR-VATNSDALUR ROCKS Contd....

Table (a) FIRST PHASE BASIC ROCKS.

Rock type locality and specimen no.	Crystal type	Köhler angles			Twin law	R.I.	Structural state	Composition (mol % An)	
		$\alpha\alpha'$	$\beta\beta'$	$\gamma\gamma'$				U-stage	R.I.
E u c r i t e s.									
B 12a	p	71½	176	108½	Cb			81	
	(p	144½	57½	135	Ab-Cb			79)	
	(pm	123	66½	146	Ab-Cb		H	63)	
	p	69	176	111	Cb			77	
	p	126½	67½	142½	Ab-Cb		H	66½	
B 17	p					$\gamma' = 1.575$			80
						$\alpha' = 1.551$			44
	g	70	163	118½	Cb		H	64½-69	
B 11	p	71	172	113	Cb			77	
	p	127½	130	73	Ab		H	63	
	g	110	93½	127½	Cb		H	44	
						$\gamma' = 1.577$			85
						$\alpha' = 1.554$			49

Contd......

Rock type locality and specimen no.	Crystal type	Köhler angles αα'	ββ'	γγ'	Twin law	R.I.	Structural state	Composition (mol % An) U-stage	R.I.
Eucrite inclusions in Early Set Cone-Sheets.									
Vi 606	p	73½	175½	108	Cb			86	
	p	67½	172	110½	Cb			77	
Vi 582	p	116	122	91½	Ab			85½	
	p	150½	57	134	Ab-Cb			80-85	
	p	72	177	109½	Cb			82	
Vi 97	p	150½	53	133	Ab-Cb			81-86	
	p	120	118	87½	Ab			80	
	p	145	61	134	Ab-Cb			79-80	
	p	67½	173½	112	Cb			74-75	
Vi 313a	p	119	117	93	Ab			83	
	p	139½	58	135	Ab-Cb			77½	
	p	69½	171½	110	Cb			77	
	pm	128	69	139	Ab-Cb		H	68	
Early Set Cone-sheets and Related Minor Intrusions.									
Vi 27	p	152	57	133	Ab-Cb			81-87	
	p	152	56½	134	Ab-Cb			81-87	
	p	147	57	136	Ab-Cb			80	

XV.

Contd......

Rock type locality and specimen no.	Crystal type	Köhler angles αα'	ββ'	γγ'	Twin law	R.I.	Structural state	Composition (mol % An) U-stage	R.I.
Early Set Cone-sheets and Related Minor Intrusions.									
Vi 60	p	71½	172½	108	Cb			85-86	
	(p	118	123½	88½	Ab			80	
	(pm				Ab		H	62 (R)	
	(p	119	119½	91	Ab			83	
	(pm				Ab		H	49 (R)	
	p	145	57½	131½	Ab-Cb			79½	
	g	68	153½	118	Cb		HT	66	
	g	128	61½	146½	Ab-Cb		HT	64	
	g	150	119½	70	Ab		HT	58 31 (R)	
	g	94	95	146½	Ab-Cb		H	52	
	p	150	53½	136½	Ab-Cb			80-85	
Vi 605	p	114½	130	87	Ab			83	
	p	150	52	136	Ab-Cb			85	
	pm	70	161	116	Cb		H	70	
Vi 453	p	146	55	135½	Ab-Cb			78-80	
	p	146½	57	139½	Ab-Cb			77	
	p	124	117	89	Ab			78-79	
	pm	69	154½	117½	Cb		H	67	
	pm							48 (R)	

Contd......

Rock type locality and specimen No.	Crystal type	Köhler angles			Twin law	R.I.	Structural state	Composition (mol % An)	
		αα'	ββ'	γγ'				U-stage	R.I.
Vi 609	g	148	122½	70	Ab		H	60	
	g	147	121½	69	Ab		H	60	
	g	94	108½	131	Cb		L	48½	
	g	98½	106½	124½	Cb		H	47	
	g	71½	108	153½	Ab-Cb		H	43	
Vi 156	g	127½	63	148	Ab-Cb		HT	63½	
	g	146½	121	67	Ab		H	59	
	g	148	127	59½	Ab		L	57	
	g	161	118	64½	Ab		H	51	
	g	95½	111	124	Cb		H	51	
Vi 348	g	69	157	115	Cb		H	69	
	g	66	157	119	Cb		H	66	
	g	66½	157½	117½	Cb		H	65	
	g	126	73½	140	Ab-Cb		H	66	
Vi 4	g	68	149	119½	Cb		H	64	
	g	80	130	120	Cb		H	59	
Gabbros									
Vi 94	p	135	114½	80	Ab		H	69½	
	p	133½	121	75½	Ab		H	68	
	p	139	120	78	Ab		H	67½	
	p	69½	156½	117½	Cb		L	65½	

Contd....

Rock type locality and specimen No.	Crystal type	Köhler angles $\alpha\alpha'$	Köhler angles $\beta\beta'$	Köhler angles $\gamma\gamma'$	Twin law	R.I.	Structural state	Composition (mol % An) U-stage	Composition (mol % An) R.I.
B 13	p	71	143½	120	Cb		H	63	
	p	72	145	120	Cb		H	63	
	p	73	142	120	Cb		H	62	
	p	140½	120½	71	Ab		H	60½	
	p	115	75	146½	Ab-Cb		H	60	
B 14	(p	121	67½	142½	Ab-Cb		H	65½)	
	(pm	100½	88	146½	Ab-Cb		H	56)	
	p	69	150½	118½	Cb		H	65	
	p	122	65	146½	Ab-Cb		H	65	
	p	141	118½	73	Ab		H	60½	
	p	106½	81½	147	Ab-Cb		H	57	
	g	102	85	147	Ab-Cb		H	56	
Vi 572	p	72½	142½	123	Cb		H	60	
Vi 186	p	106	84	148	Ab-Cb		H	56	
	p	110	76½	154	Ab-Cb		L	56	
	p	88½	116	127	Cb		H	50½	
Vi 419	p	122½	68	144½	Ab-Cb		H	64	
	p	118	73½	146	Ab-Cb		H	61	
	p	113½	79	145	Ab-Cb		H	59	
						$\gamma' = 1.564$			61½
						$\alpha' = 1.551$			44
Vi 610						$\gamma' = 1.565$			63
						$\alpha' = 1.552$			46

Contd.....

Rock type locality and specimen No.	Crystal type	Köhler angles $\alpha\alpha'$	Köhler angles $\beta\beta'$	Köhler angles $\gamma\gamma'$	Twin law	R.I.	Structural state	Composition (mol % An) U-stage	Composition (mol % An) R.I.
Vi 265/1	p	151	122	69½	Ab		H	58	
	p	78½	130	121½	Cb		H	58	
Vi 2	p	75½	140½	116½	Cb		H	62½	
	p	116	76	146½	Ab-Cb		H	60	
	pm							43 (R)	
	p	119	78½	145½	Ab-Cb		H	59½	
	p	76	134½	121½	Cb		H	59½	
	p	78	137	123	Cb		H	58	
						$\gamma' = 1.563$			60
						$\alpha' = 1.546$			34
Vi 575/7a	p	138½	59	138	Ab-Cb			75	
	p	75½	147	117½	Cb		H	63	
	p	75½	145	116½	Cb		H	63	
	p	75	142	119	Cb		H	62	
	p	77½	143	118	Cb		H	62	
	g	110	81	135½	Cb		H	39	
Vi 575/13	p	128	73½	133	Ab-Cb		H	64	
	p	80	131	125½	Cb		H	54	
	g					$\gamma' = 1.562$			58
	g					$\alpha' = 1.547$			36

Rock type locality and specimen No.	Crystal type	Köhler angles			Twin law	R.I.	Structural state	Composition (mol % An)	
		αα'	ββ'	γγ'				U-stage	R.I.
Vi 575/6	p	154	119½	66	Ab		H	55	
	p	92	96	147½	Ab-Cb		H	53	
	p	99½	113	122½	Cb		H	52	
	p	87	115½	126	Cb		H	51	
	p	98	104	128½	Cb		H	48	
	p	111	95½	127	Cb		H	44	
						γ'= 1.558			50
						α'= 1.547			36
Vi 170	p					γ'= 1.565			63
						α'= 1.548			38

OPTICAL PROPERTIES AND COMPOSITIONS OF PLAGIOCLASES FROM THE VIDIDALUR-VATNSDALUR ROCKS.

Table (b) FIRST PHASE INTERMEDIATE AND HYBRID ROCKS.

Specimen number	Crystal type	Köhler angles			Twin law	R.I.	Structural state	Composition (mol % An)	
		$\alpha\alpha'$	$\beta\beta'$	$\gamma\gamma'$				U-stage	R.I.
Diorite.									
Vi 215	p	91½	97½	154	Ab-Cb		L	52	
	p	157½	130½	55	Ab		L	52½	
	p	82½	104	153	Ab-Cb		H	45	
	p	73	116	154½	Ab-Cb		H	41	
Vi 401	p	155	119	66	Ab		H	53	
	p	163½	120	57½	Ab		H	47	
	p	164	120	60	Ab		H	47	
	p	54½	129½	162	Ab-Cb		H	34½	
Vi 116	p	156½	123	64	Ab		H	52½	
	p	93½	94	149	Ab-Cb		H	51	
	p	98	88½	150	Ab-Cb		H	51	
	p	158½	121	62½	Ab		H	51	
	p	94	108	126	Cb		H	49	
	p	94½	109½	125	Cb		H	47	
Vi 399	p	168	120	63	Ab		H	47	
	p	100½	99	129	Ab		H	46	
	p	177	128	49½	Ab		H	38	
	p	66	119	157	Ab-Cb		H	38	
						$\gamma' = 1.555$			44
						$\alpha' = 1.539$			21

Contd.....

Specimen number	Crystal type	Köhler angles			Twin law	R.I.	Structural state	Composition (mol % An)	
		αα'	ββ'	γγ'				U-stage	R.I.
Basic Granophyre (H_I).									
Vi 265/14	p	82	108½	156	Ab-Cb		H	42	
	p	170	126	54½	Ab		H	41½	
	p	74	111	156	Ab-Cb		H	41	
	p	170	130	55	Ab		H	40	
	p	46	138½	157½	Ab-Cb		H	23	
						$\gamma' = 1.556$			46
	pm					$\beta = 1.541$			15
	pm							12 (R)	
Vi 265/16	p	69	111½	156½	Ab-Cb		H	44	
	p	173	121½	58	Ab		H	43	
	p	69½	117	155	Ab-Cb		H	40	
	p	173	128½	54½	Ab		H	40	
	p	117	84	131	Cb		H	39	
	p	176	140	41	Ab		LT	37½	
	p	120	81½	139½	Cb		T	37	
	p	112½	83	139	Cb		T	39	
Granite (H_G).									
Vi 615	p	133½	56½	148½	Cb		H	26	
	p	161½	35	150	Cb		HT	5½	
	p	29	154½	168	Ala-A		HT	0-5	
	p					$\gamma' = 1.534$			5
Vi 265/23	p				Ab		H	25-28 (R)	
	pm				Ab		H	20 (R)	

OPTICAL PROPERTIES AND COMPOSITIONS OF PLAGIOCLASES FROM THE VIDIDALUR-VATNSDALUR ROCKS.

Table (c) FIRST PHASE ACID ROCKS.

Specimen number	Crystal type	Köhler angles $\alpha\alpha'$	Köhler angles $\beta\beta'$	Köhler angles $\gamma\gamma'$	Twin law	R.I.	Structural state	Composition (mol % An). U-stage	Composition (mol % An). R.I.
Va 35	p	72	115	153	Ab-Cb		H	41½	
	p	117	87½	129	Cb		H	41½	
	p	70½	116	153	Ab-Cb		H	41	
	p	114½	85½	131	Cb		H	40	
Vi 178	p	60½	124	158	Ab-Cb		H	36	
	p	50	136	157	Ab-Cb		H	31	
	p	126½	69	156½	Cb		HT	30	
	p	172½	140	39½	Ab		H	27	
	p	173½	145½	38½	Ab		H	26	
	p	172	151½	32½	Ab		H	23	
	p					β=1.549			31
	pm					α'=1.536			16
Vi 174	p	176	147	34½	Ab		H	27	
	p	171	161	21	Ab		H	19	
	p	170	167	26	Ab		H	17	
	pm	168½	174	12	Ab		H	14	
	pm					β =1.540			11
	g						H	20 (R)	
Vi 33	p	169	152½	29	Ab		H	20	
	p	170	164½	20	Ab		H	17	
	p	169½	163	17½	Ab		H	16½	
						γ'=1.544			22

Contd.....

Specimen number	Crystal type	Köhler angles			Twin law	R.I.	Structural state	Composition (mol % An).	
		αα'	ββ'	γγ'				U-stage	R.I.
Vi 39	p	176½	151	31	Ab		H	24	
	p	171½	149½	33	Ab		H	22	
	p	173½	156	20½	Ab		H	21	
	p					β = 1.550 - 1.551			32-33
Vi 409c	p	139	47½	157½	Cb		H	20	

xxv

OPTICAL PROPERTIES AND COMPOSITIONS OF PLAGIOCLASES FROM THE VIDIDALUR-VATNSDALUR ROCKS.

Table (d) SECOND PHASE BASIC ROCKS.

Specimen number	Crystal type	Köhler angles $\alpha\alpha'$	$\beta\beta'$	$\gamma\gamma'$	Twin law	R.I.	Structural state	Composition (mol % An) U-stage	R.I.
Eucrites.									
Vi 95	p	117	121	92	Ab			85	
	p	149½	59½	132	Ab-Cb			84½	
	p	147½	53½	139	Ab-Cb			76-78	
	p	67	171½	111	Cb			74	
	pm	82½	123½	120	Cb		H	55	
	g	95	113½	123½	Cb		H	52	
						γ' = 1.580			90
						α' = 1.552			46
Late-Set Cone-sheets.									
Vi 551b	(p	115½	119½	93	Ab			87	
	(pm	131	123	81	Ab		L	71	
	p	119	121	93	Ab			86	
	p	150	58	133½	Ab-Cb			80-85	
	(p	121½	118½	91	Ab			83	
	(pm	179	39	142	Ab		II	31	
	pm	122½	74	146	Ab-Cb		H	62	
	pm	73½	113	152	Ab-Cb		H	43½	
Vi 85	p					β = 1.574			78½
	g	137	122	75½	Ab		H	67	
	g	72½	147½	115½	Cb		H	65	
	g	112	78	145½	Ab-Cb		H	60	
						γ' = 1.577			85
						α' = 1.548			38

Contd..

Specimen number	Crystal type	Kohler angles αα'	ββ'	γγ'	Twin law	R.I.	Structural state	Composition mol % An U-stage	R.I.
Vi 28	p	115	125	91	Ab			88	
	p	118	123	92	Ab			86	
	p	118½	122	91	Ab			84	
	pm	70	161½	113½	Cb		H	71½	
	pm	137½	122	75	Ab		H	67	
	pm	88½	112½	126	Cb		H	51	
	g	131	120	81½	Ab		H	73	
	g	64	167	115	Cb		H	71½	
	g	68½	157	113½	Cb		H	70	
	g	96	108½	129½	Cb		H	47	
Vi 304	p	146	58	135	Ab-Cb			78½	
	g	141	126½	68	Ab		L	63	
	g	79	143	115	Cb		H	63	
	g	76½	142½	120	Cb		H	61	
	g	79	139½	119½	Cb		H	60	
	g	77½	123	129	Cb		L	54	
	g	86½	120	123	Cb		H	54	
	g	163½	120	62½	Ab		H	48½	
	g					$\gamma' = 1.562$			58
	g					$\alpha' = 1.545$			32

XXVII

Contd.....

Specimen number	Crystal type	Köhler angles			Twin law	R.I.	Structural state	Composition (mol % An)	
		$\alpha\alpha'$	$\beta\beta'$	$\gamma\gamma'$				U-stage	R.I.
Vi 320	p	119	122	89	Ab			80	
	g	102½	88	144	Ab-Cb		H	58	
	g	152	130	57½	Ab		L	55	
	g	87½	126	122	Cb		H	55	
	g	170	120	59½	Ab		H	46	
	g	107½	84½	141	Cb		H	40	
Vi 193	g	70	153	119	Cb		HT	65	
Vi 76	p	72	165½	108½	Cb			80	
	p	129	119½	84	Ab		T	74	
	p	68½	167	112½	Cb		L	73	
	g	72½	144	120	Cb		H	60½	
	g	74½	137	121	Cb		H	60	
	g	152	122	65½	Ab		H	55	
	pm	69	119	151½	Ab-Cb		H	42	
						γ'= 1.576			82½
						α'= 1.549			40
Sf 2	g					γ'= 1.560			54
	g					α'= 1.545			32½
C 1b	g					γ'= 1.561			56
	g					α'= 1.547			36
C 2	x	112	81½	138½	Cb			38	

Contd....

Specimen number	Crystal type	Köhler angles αα'	ββ'	γγ'	Twin law	R.I.	Structural state	Composition (mol % An) U-stage	R.I.
Basalt Lava.									
TFB	p	$137\frac{1}{2}$	$124\frac{1}{2}$	71	Ab		L	64	
	p	$118\frac{1}{2}$	80	$144\frac{1}{2}$	Ab-Cb		H	61	
Gabbros.									
Va 33	p	$72\frac{1}{2}$	$152\frac{1}{2}$	116	Cb		H	$65\frac{1}{2}$	
	p	$142\frac{1}{2}$	$123\frac{1}{2}$	70	Ab		H	$62\frac{1}{2}$	
	p	71	144	$120\frac{1}{2}$	Cb		H	62	
	p	76	141	119	Cb		H	61	
	p	150	123	65	Ab		H	55	
						$\gamma' = 1.569$			70
						$\alpha' = 1.549$			40
Hnj						$\gamma' = 1.567$			67
						$\alpha' = 1.549$			40
Hj 200	p	134	119	78	Ab		H	$69\frac{1}{2}$	
	p	133	$117\frac{1}{2}$	82	Ab		H	67	
	p	125	69	$142\frac{1}{2}$	Ab-Cb		H	66	
	p	121	70	$144\frac{1}{2}$	Ab-Cb		H	$63\frac{1}{2}$	
Hj	p	139	59	143	Ab-Cb		L	$69\frac{1}{2}$	

OPTICAL PROPERTIES AND COMPOSITIONS OF PLAGIOCLASES FROM THE VIDIDALUR-VATNSDALUR ROCKS.

Table (e) SECOND PHASE ACID ROCKS.

Specimen number	Crystal type	Köhler angles $\alpha\alpha'$	$\beta\beta'$	$\gamma\gamma'$	Twin law	R.I.	Structural state	Composition (mol % An) U-stage	R.I.
Vi 200	p	172½	124	55½	Ab		H	41½	
	p	128	61½	151	Cb		H	31	
	p	177	144	37	Ab		H	29½	
	p	177	142½	38	Ab		H	29½	
Vi 201	p	176	136½	43½	Ab		H	32	
	p	129	65	143	Cb		H	31½	
	p	176	139½	41	Ab		H	31	
	p	176	138	41½	Ab		H	31	
Vi 172	p	178	128	51	Ab		H	37	
	p	130½	68	137½	Cb		H	33	
	p	128	65	143	Cb		H	31½	
	p	130½	65	140½	Cb		H	31½	
	p	50	136½	156	Ab-Cb		H	31	
	p	176	139½	42	Ab		H	31	
	p	127½	61	146	Cb		H	30	
	p	175½	138	40	Ab		H	30	
	p	131	58	147	Cb		H	28	
	p	173½	140½	39	Ab		H	27	
	g	132½	53½	154½	Cb		H	25	
	x	131	67½	138½	Ab-Cb		H	69	
	p					β = 1.550			30
						β = 1.547			27½
Vi 168	p	51	135½	156½	Ab-Cb		H	32	
	p	175½	142	40	Ab		H	28	
	g	47½	138	161	Ab-Cb		H	23½	
	g	46	139	158	Ab-Cb		H	23	
A 14	p	52	133½	159	Ab-Cb		H	31½	
	gm				Ab		H	7 (R)	
						γ = 1.550			34
						α' = 1.531			7

Contd.....

Table (f). BASALT LAVA

Specimen number	Crystal type	Köhler angles			Twin law	R.I.	Structural state	Composition (mol % An)	
		$\alpha\alpha'$	$\beta\beta'$	$\gamma\gamma'$				U-stage	R.I.
Va 1	p	110½	124	91	Ab			92-93	
	p	114	125	92	Ab			92	
	p	113	119	92	Ab			c.90	
	p	113	122½	89	Ab			86	
	p					$\gamma' = 1.581$			92
	pm					$\alpha' = 1.568$			76½

Part 2, Table A. CHEMICAL ANALYSES OF TERTIARY IGNEOUS ROCKS FROM ICELAND, THE HEBRIDES AND NORTHERN ENGLAND.

KEY TO SPECIMENS IN TABLE A.

<u>Southwestern Iceland</u>

1. Light-coloured gabbro (eucrite), Vesturhorn, (Cargill *et al*., 1928, no. 82, p. 517).

2. Basic quartz-hornblende-diorite, near Rustanof, Vesturhorn, (Ibid., no. 68, p. 514).

3. Acid quartz-diorite with granitic texture, Vesturhorn, (Ibid., no. 157, p. 513).

4. Graphic hornblende-granodiorite, Vík, Austurhorn, (Ibid., no. 130, p. 518).

5. Hornblende-granophyre, Kastardal, Vesturhorn, (Ibid., no. 74, p. 513).

6. Gabbro, west of Hvalnes farm, Austurhorn (Blake, 1966, Table 2, no. 12).

7. Banded gabbro, west Hvalnesfjall, Austurhorn, (Ibid., no. 15).

8. Margin of tholeiite pillow, Krossanes, Austurhorn, (Ibid., no. 19).

9. Interior of same pillow as 8, (Ibid., no. 20).

10. Hornblende-granophyre, Hvasshjalli, Austurhorn, (Ibid., no. 7).

11. Granite, Hvalnes, Austurhorn, (Ibid., no. 3).

12. Ferroaugite-granophyre, Hvalnesskriður, Austurhorn, (Ibid., no. 2).

13. Average of 12 hybrid rocks, Slaufrudal (Beswick, 1965).

14. Average of 37 granophyres, Slaufrudal (Beswick, 1965).

15. Average Icelandic pitchstone (Carmichael and MacDonald, 1961, Table 14, B).

<u>The Hebrides and Northern England.</u>

16. Tachylite border of Teesdale Cleveland-type tholeiite dyke (Holmes and Harwood, 1929, p. 40, P).

17. Inninmorite inclined sheet, near Pennyghael, Isle of Mull (Tyrrell, 1917, Table II, no. 4).

18. Inninmorite-Pitchstone from lava flow near Bourblage, Ardnamurchan, (Richey *et al*., 1930, Table III, no. II).

The Hebrides and Northern England contd.....

19. Acid pitchstone, Glen Shurig type, Isle of Arran (Tyrrell, 1928, Table VII, no. 16).

20. Acid pitchstone, Judd's No. II dyke, Isle of Arran (Ibid., Table VII, no. 15).

TABLE A

CHEMICAL ANALYSES OF TERTIARY IGNEOUS ROCKS FROM ICELAND, THE HEBRIDES AND NORTHERN ENGLAND.

	1	2	3	4	5	6	7	8	9
SiO_2	47.30	53.55	64.74	66.66	70.36	40.4	45.4	54.3	54.1
TiO_2	0.58	1.48	0.35	0.25	tr	6.1	2.3	2.1	2.19
Al_2O_3	25.04	17.45	17.04	14.89	14.85	12.4	19.6	14.7	14.8
Fe_2O_3	0.93	3.60	1.49	2.74	2.34	7.1	5.6	2.6	2.7
FeO	3.41	6.98	3.87	3.22	2.36	11.0	6.1	7.8	7.9
MnO	tr	0.25	0.06	tr	0.18	0.22	0.12	0.21	0.15
MgO	4.00	3.47	1.33	1.04	0.44	7.3	4.3	3.8	3.8
CaO	15.92	6.53	3.45	3.20	1.82	12.4	12.3	7.2	7.2
Na_2O	1.56	3.23	4.17	4.44	4.25	1.8	2.7	5.2	4.1
K_2O	0.42	1.72	2.77	2.72	2.91	0.3	0.4	1.0	1.4
P_2O_5	0.10	0.39	0.21	0.18	0.05	0.1	0.17	0.53	0.48
H_2O^+	0.54	0.82	0.30	0.37	0.21	1.3	0.9	1.2	1.2
H_2O^-	0.12	0.40	0.10	0.16	0.11	0.2	0.1	0.1	0.1
CO_2	-	-	-	-	-	-	-	-	-
F	-	-	-	-	-	-	-	-	-
S	-	0.03	0.04	-	-	-	-	-	-
Total	99.92	99.90	99.92	99.87	99.88	100.6	100.0	100.7	100.1

TABLE A (Continued)

	10	11	12	13	14	15	16	17
SiO_2	66.5	70.9	72.1	70.5	74.8	70.5	55.19	64.13
TiO_2	0.59	0.34	0.35	0.69	0.22	0.3	1.03	1.19
Al_2O_3	15.2	14.3	12.7	14.1	12.5	12.4	12.30	13.15
Fe_2O_3	2.1	2.1	2.4	1.39	1.95	1.1	10.23	1.08
FeO	3.1	1.5	1.6	1.20	0.43	1.9		6.31
MnO	0.13	0.04	0.16	0.04	0.05	0.1	0.63	0.27
MgO	0.78	,0.29	0.15	0.66	0.03	0.3	4.12	1.08
CaO	2.63	1.21	1.26	1.63	0.57	1.4	7.53	3.62
Na_2O	5.7	5.7	5.1	4.42	4.45	4.6	2.13	3.64
K_2O	2.7	3.2	3.6	4.20	4.02	2.8	1.30	2.32
P_2O_5	0.38	0.06	0.12	0.10	0.04	0.05	-	0.31
H_2O^+	0.4	0.3	0.8	0.67	0.67	3.8		2.71
							1.55	
H_2O^-	0.05	0.1	0.05	-	-	0.8		0.36
CO_2	-	-	-	-	-	-	3.64	-
Total	100.3	100.0	100.4	99.60	99.73	100.05	99.65	100.26 (includes 0.09% BaO)

TABLE A (continued).

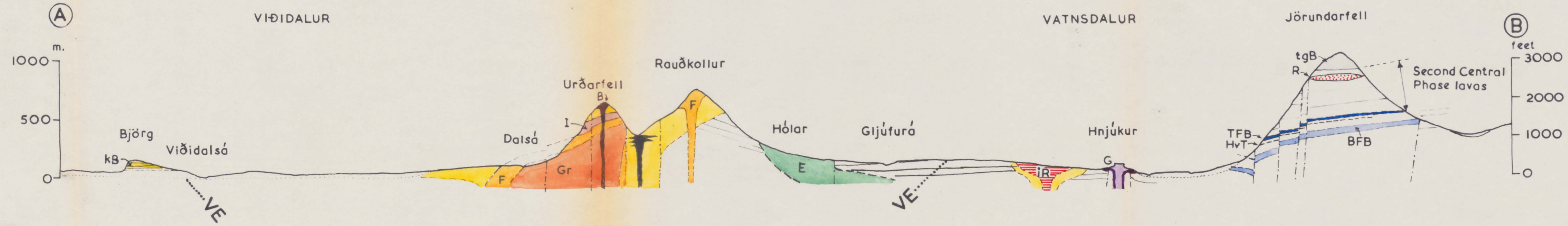
	18	19	20
SiO_2	66.06	71.51	72.33
TiO_2	1.08	0.33	0.30
Al_2O_3	13.14	10.55	10.45
Fe_2O_3	2.27	0.79	1.00
FeO	2.84	2.22	2.14
MnO	0.31	0.42	0.50
MgO	0.77	0.52	0.11
CaO	2.75	1.52	1.44
Na_2O	4.28	4.12	4.09
K_2O	1.54	3.48	3.49
P_2O_5	0.09	0.24	0.16
H_2O^+	3.38	4.07	4.02
H_2O^-	0.74	0.19	0.16
CO_2	0.37	-	-
Total	99.80	100.04	100.27
	(includes 0.02% organic matter and traces of BaO, Li_2O, FeS_2 and SO_3)	(includes 0.08% BaO)	(includes 0.08% BaO and a trace of Li_2O)

SECTIONS BASED ON MAPS ① and ②

Vertical scale 2 x horizontal

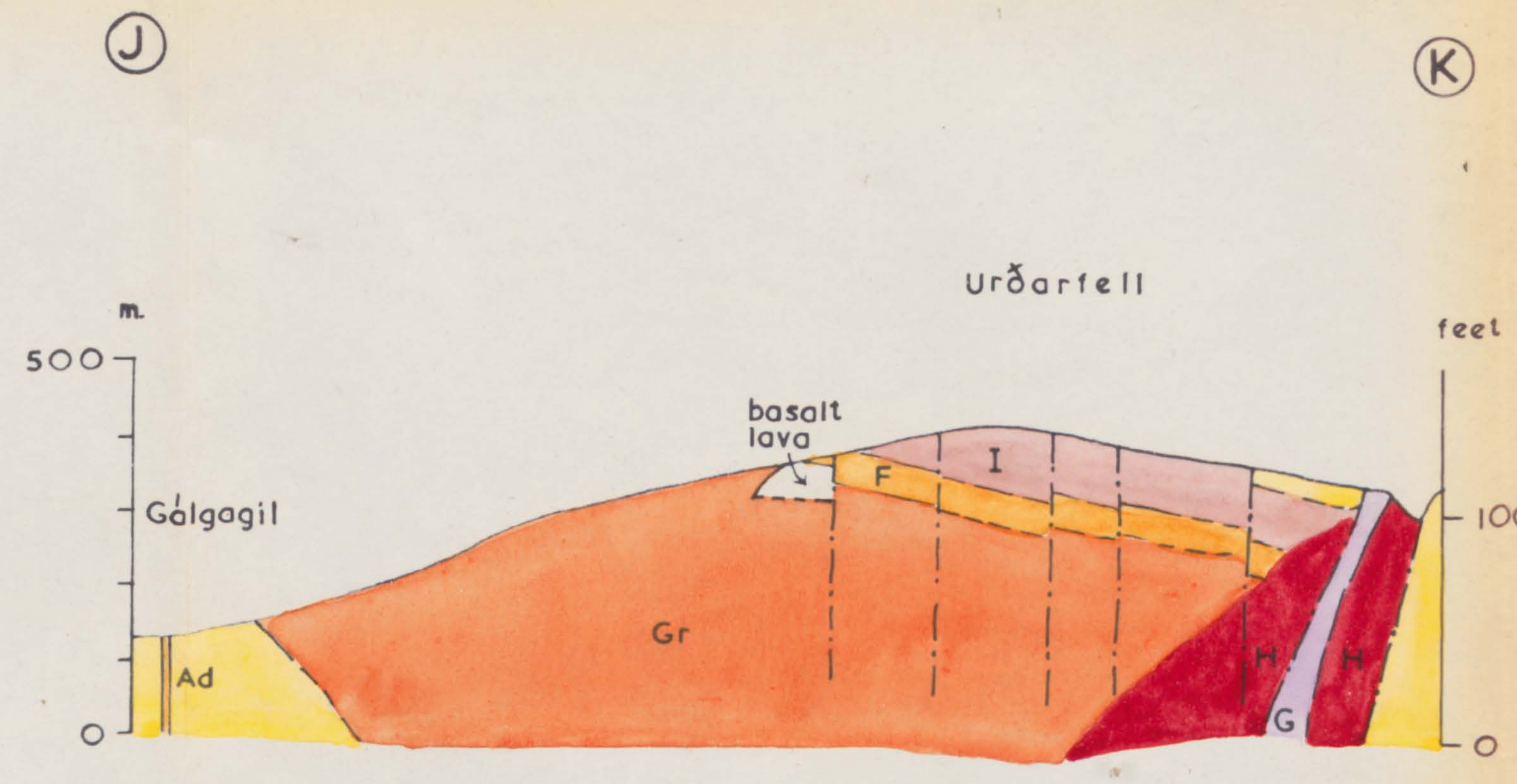
MAP ①

Section along line A–B

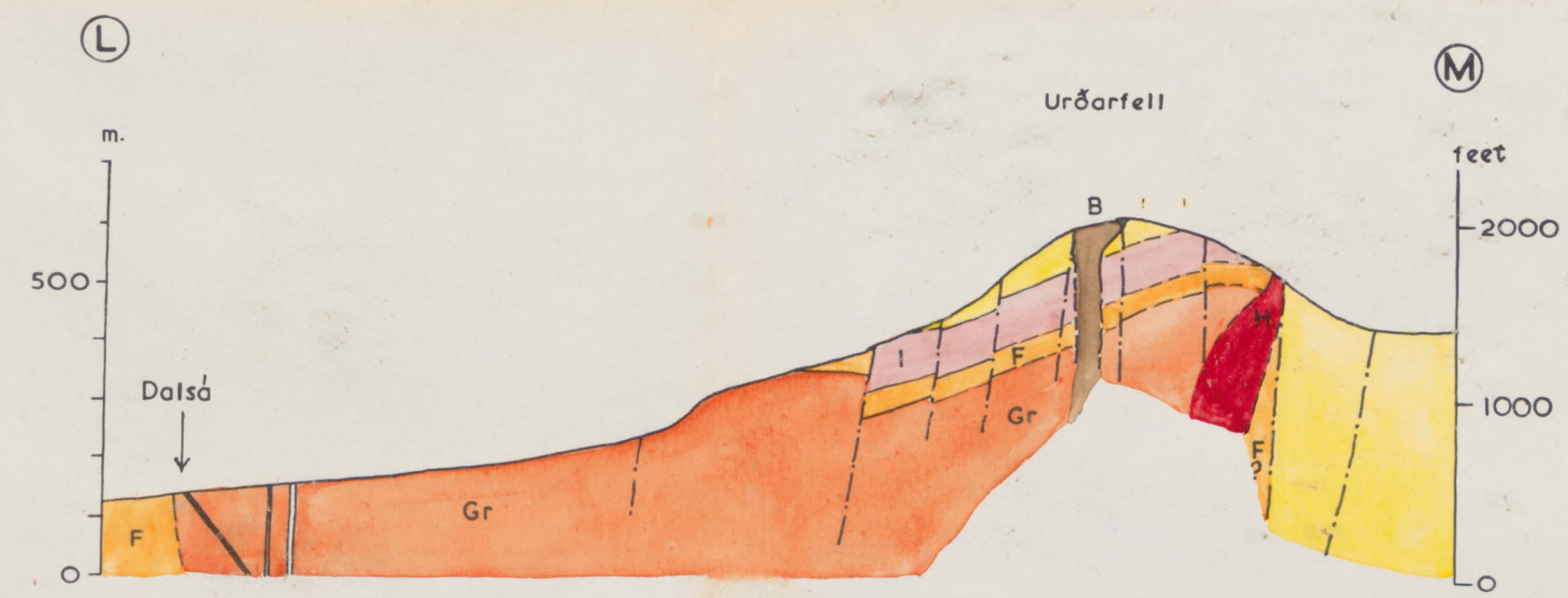


Section along line C–D

MAP ②



Section along line J–K



Section along line L–M

Vertical scale equal to horizontal

CHART ①

STRATIGRAPHY OF THE VIÐIDALUR-VATNSDALUR AREA

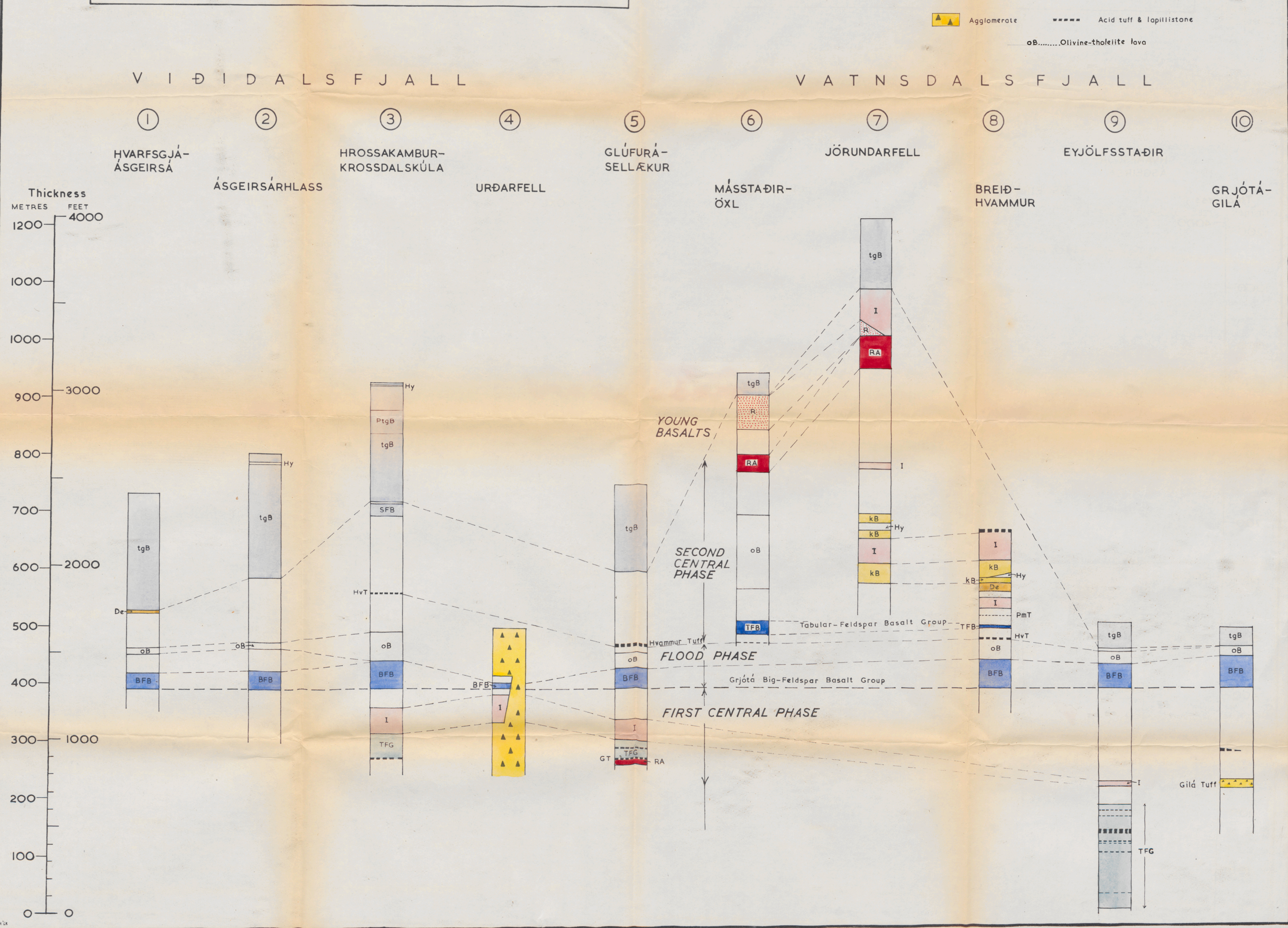


CHART 2

PLAGIOCLASES of the VIÐIDALUR-VATNSDALUR INTRUSIONS (from data in APPENDIX, Part 1)